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U. S. DEPARTMENT OF AGRICULTURE,

BUREAU OF SOILS—BULLETIN No. 43.

MILTON WHITNEY, Chief.

RECLAMATION OF ALKALI LAND IN SALT LAKE VALLEY, UTAH

BY

CLARENCE W. DORSEY.

WASHINGTON:

GOVERNMENT PRINTING OFFICE.

1907.

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LETTER OF TRANSMITTAL.

U. S. DEPARTMENT OF AGRICULTURE,
BUREAU OF SOILS,
Washington, D. C., April 30, 1907.

SIR: I have the honor to transmit herewith the manuscript of a report entitled Reclamation of Alkali Land in Salt Lake Valley, Utah, and to recommend that it be published as Bulletin No. 43 of this Bureau.

Very respectfully,

MILTON WHITNEY,
Chief of Bureau.

Hon. JAMES WILSON,
Secretary of Agriculture.

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RECLAMATION OF ALKALI LAND IN SALT LAKE VALLEY, UTAH.

INTRODUCTION.

Sixty years after the hardy Mormon pioneers made their appearance in Salt Lake Valley there yet remains an extensive body of land, extending westward from the Jordan River to the shores of Great Salt Lake, that contributes but little to the agricultural importance of Utah. At first it appears strange that such extensive tracts of level land should remain undeveloped with Salt Lake City close at hand offering perhaps the best market to be found in the West for all classes of farm produce. On the east side of the valley, situated the same distance from Salt Lake City, farm land finds a ready sale at prices of more than $200, and even $300, an acre, and produces plentiful crops of great variety. It was in this part of the valley that irrigation was first practiced in Utah. The crude beginning is described by Mr. E. G. Wooley, a bishop in the Mormon Church, in the following words: "The pioneers came into the valley in July, 1847. The advance company drifted right down upon the site of Salt Lake City. They went to work the first day, ran a plowed ditch out of City Creek, and started the water out on the ground and planted some potatoes the same day."

The reason for the backward development of the large body of land between the river and Great Salt Lake lies in the fact that the soils contain soluble salts in such quantities that useful crops can not be grown. Once the salt or alkali is removed the soils will be found as rich as those which enabled the industrious pioneers to prosper in the manner they have done. That reclaiming these soils is not only possible but practicable will be shown in the following pages by describing the reclamation of one of the most strongly impregnated tracts of alkali land found in the valley. After detailing the work on this tract the practical application of this experimental work to the damaged lands of the valley will be shown; that is, we will consider just what steps the farmer must take to make productive the extensive areas of alkali waste land.

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DESCRIPTION OF SALT LAKE VALLEY.

Salt Lake Valley lies in northern-central Utah and comprises the greater part of the western half of Salt Lake County. The valley attains a maximum width of something more than 20 miles from east to west and a somewhat greater length from north to south. The valley is characterized by wide stretches of comparatively level land, sloping gently to the north and west, and by a number of slight ridges that rise only a few feet above the general valley floor. On the margins of the valley the ridges are more pronounced. Salt Lake City, 14 miles east of Great Salt Lake, has an elevation of 4,253 feet. The Wasatch Range rises abruptly above the valley on the east, and many peaks attain an elevation of over 11,000 feet. To the south the valley gradually converges into the Jordan Narrows. On the southwest the Oquirrh Mountains rise 3,000 to 4,000 feet above the valley floor. Bordering the valley on the north and west occurs Great Salt Lake, a shallow body of water covering an area of about 2,000 square miles. Great Salt Lake constitutes only a remnant of a former lake that once attained an area of nearly 20,000 square miles. This prehistoric body of water, named Lake Bonneville in honor of the intrepid explorer, at one time stood 1,000 feet higher than the present lake level. Evidences of the former lake are everywhere visible, even to the untrained observer, in the many pronounced shore lines that stand out in bold relief hundreds of feet above the present valley floor. The Lake Bonneville basin, together with many inclosed drainage basins in Nevada, Oregon, and California, broken by parallel ranges of mountains, constitutes the physiographic region known as the Great Basin, the character and extent of which was first made known by the explorations of Fremont.[a]

Salt Lake Valley, in common with other extensive interior valleys, has what may be termed a true continental climate, relieved to some extent by the modifying influence of Great Salt Lake.[b] Temperatures at Salt Lake City range from −20° F., the lowest recorded minimum, to 102° F., the highest recorded maximum, with 52° as the annual mean temperature. The precipitation during the period 1874 to 1903 for the driest year was 10.2 inches and for the wettest year 23.5 inches, with 15.8 inches representing the average rainfall for the period. The spring months, March, April, and May, receive the greatest rainfall, with an average of nearly 2 inches each month. The summer months receive the least rainfall, the entire three months receiving only 2 inches of rain. The average depth of snow for the year is slightly more than 50 inches. The relative humidity is low, especially during the summer months, at which time the percentage of

[a] Lake Bonneville, Monograph of U. S. Geol. Survey, by G. K. Gilbert, 1890.
[b] Bul. Q, U. S. Weather Bureau, 1906.

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possible sunshine is the highest of the year. These conditions of light rainfall, low relative humidity, and high temperatures hasten evaporation during the summer months, making irrigation necessary to insure the best results. Dry farming is possible only for such crops as mature before the hot summer sets in and is practiced but little in the valley proper. Considerable dry farming is carried on in the valleys of the lower foothills and on the higher bench lands, where the rainfall is appreciably greater.

SOIL AND ALKALI CONDITIONS IN SALT LAKE VALLEY.

In 1899 the Bureau (then Division) of Soils, in cooperation with the Utah experiment station, made a soil survey of that portion of the valley lying west of Jordan River. This survey comprised an area of over 250 square miles, but did not include the best farming districts of the valley lying east of the Jordan River. This should be remembered in the discussion of the alkali problems, since the lands east of the river are but little affected by alkali. There are some alkali areas south of Salt Lake City, especially in the bottom along the river, but the greater extent of land east of the river has good slope, which implies fair natural drainage with the tendency for the salts originally contained in the soils to be washed to lower levels. It is this part of the valley that has had the greatest agricultural development and is at present in a prosperous condition.

This soil survey was made by Frank D. Gardner and John Stewart, and the report was published in the Field Operations of the Division of Soils, 1899, and as Bulletin 72 of the Utah experiment station. The soils were found to have been formed by material brought down from the mountains and from sediments of ancient Lake Bonneville, all of which have been materially modified by inflowing streams from the mountains and by the advance and recession of Great Salt Lake. On account of the manner of their formation the soils vary greatly in character. In the lower part of the valley the lacustrine deposits are very deep, no rock or gravel being found at a depth of a hundred or more feet. As we approach the foothills gravel and rock are plentiful and often crop out at the surface, and the depth of lake sediments diminishes and in many places none at all is found.

The soils are fertile, but in their natural condition support only a meager vegetation, because they are either too dry or contain too much alkali. On the higher levels, where little salt is present, sagebrush forms the chief growth, while in the lower parts of the valley, where there is more moisture and much salt, greasewood, salt grass, and other salt-loving vegetation forms the principal growth.

The most important soil type was found to be the Jordan sandy loam, a light-colored sandy loam, with a depth of several feet, overlying clay. Where this class of soil is above irrigation canals and in the

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irrigated districts wherever the subsoil water is 10 feet or more below the surface it is generally free from excessive quantities of alkali. In the low areas, especially in the northern part of the valley, there is much alkali in the lower depths of soil. This soil is easily cultivated and where free from alkali is a desirable soil for any crops grown in the valley.

On the higher slopes of the southern part of the valley occur extensive areas of a gravelly loam soil. This soil is usually free from alkali, but on account of the large amount of gravel and high position is difficult to irrigate. Much of this soil is dry-farmed to wheat with good results in years of abundant rainfall.

Another important type of soil was found to be the Jordan loam. It comprises an area of about 50 square miles, most of which is below the present canal systems. It is a heavy loam overlying a clay subsoil. Where free from alkali and under cultivation the Jordan loam is an excellent soil, but the water table is generally within a few feet from the surface and the alkali content is considerable in the lower depths of soil.

The Jordan clay occupies about 35 square miles, occurring largely in low positions, usually from 4 to 8 feet below the land immediately adjoining. It is level and wet and rarely supports any vegetation. It represents what was formerly the floors of lagoons near the shore of the lake, and in many places it is now the floor of draws extending like wide irregular canals back into the land for miles. On account of the clayey nature of this soil, the low undrained position, and high alkali content it is at present not suited to agricultural purposes. Other less important classes of soils were found that need not be considered.

In a number of small areas hardpan was found, occurring principally in connection with the sandy loam soils. The hardpan usually is encountered at an average depth of 18 inches and ranges in thickness from 2 to 18 inches. It is composed of material similar to that immediately above and below it, cemented by lime carbonate. When dry this hardpan is hard and difficult to penetrate, but after irrigation has been practiced for some time it readily softens and is pervious to water and the roots of plants. Usually it was observed that the soil above the hardpan was free from alkali, while below the hardpan the salt content was much greater.

The main water supply for the western part of the valley is derived directly from Utah Lake, a large body of fresh water lying south of Salt Lake Valley. It has an area of approximately 125 square miles but is rather shallow. It is fed largely by short mountain streams derived from melting snow. While the inflowing streams contain but little soluble salts seepage from surrounding lands affects the salt content of the lake. The outlet of Utah Lake is the Jordan River,

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from which several canals are taken out. While the salt content of the Jordan varies at different points, depending to some extent on the amount of seepage water it receives from irrigated land, it is usually of good quality. Analyses of the water from Jordan River at the time the survey was made, 1899, showed the presence of from 80 to 110 parts per 100,000, consisting mainly of the chlorides and sulphates of sodium and calcium.

The distribution of the alkali was found to depend largely upon the topography of the valley as well as upon the character of soils. The accompanying sketch map (fig. 1) shows the extent of lands containing more than 0.60 per cent of alkali. As a rule the greatest accumulations of alkali were found in the heavier textured soils that occupy the lower portions of the valley. The heavy clay soils that have within recent years been covered by Great Salt Lake almost without exception contain excessive quantities of alkali. In these areas also the water table stands within a few feet of the surface. The heavy nature of the soil, the shallow ground water, and the low position have caused these soils to retain the salts added by contact with the saline waters of the lake. On the higher ridges in the valley and on the more sloping lands bordering the valley the ordinary precipitation in the form of rain or snow has leached away considerable of the salts orignally contained.

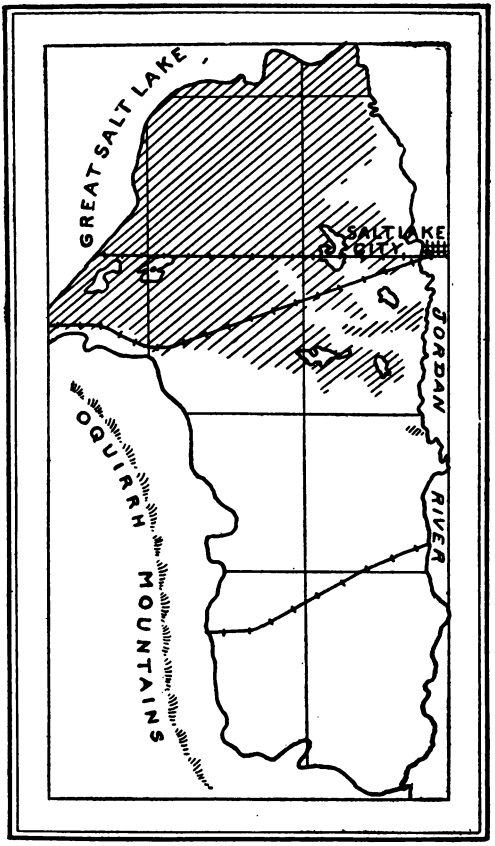

FIG. 1.—Sketch map showing distribution of alkali in Salt Lake Valley. Hatch lines cover area affected.

It was found that the character of the soil and the depth to standing water were the most important factors in determining the vertical distribution of alkali in the soil. On sandy soils with the water table several feet below the surface the top soil was generally free from alkali, but it increased in amount in the lower depths. Where the

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water stood within 3 feet or less from the surface the greater part of the alkali was concentrated at or near the surface.

The source of the alkali is probably the waters of Great Salt Lake (which within the memory of the older inhabitants has covered much of the low-lying lands) or in the case of the more elevated lands the waters of Lake Bonneville. The alkali is largely composed of sodium chloride with a smaller quantity of sodium sulphate and a small percentage of the chlorides, sulphates, and carbonates of calcium and magnesium. Sodium carbonate, black alkali, is often found, generally in small quantities.

During the progress of the survey in 1899 it was found that an area of more than 77,000 acres was practically free from alkali. This large area comprises the more sloping lands where good natural drainage and porous soils have prevented injurious accumulations of alkali. Seventeen thousand acres contained sufficient alkali in the first 6 feet to render certain precautions necessary to prevent injury of crops. Much of this land occurs south of Twelfth South street road where seepage and surplus waters have formed a chain of lakes. In the vicinity of these lakes the ground water is within a few feet of the surface, and unless some form of drainage is provided accumulation of alkali will undoubtedly increase. Where this amount of alkali (0.25 to 0.60 per cent) is found on higher, better drained soils no serious damage should result provided the surface be carefully leveled and all water be supplied in the form of heavy surface flooding at infrequent intervals.

Seventeen thousand acres was found to contain from 0.60 to 1 per cent of alkali, occurring in sandy soils with the water table usually about 4 feet from the surface. Generally the greater part of the alkali is concentrated in the lower depths of soil and attempts to cultivate this land are successful for a few years. With the rise of the ground water the alkali usually rises to the surface and many failures have resulted after cultivating such land, owing to the concentration of too much alkali in the upper layers of soil.

By providing even a limited amount of drainage and heavy surface irrigation many of these failures could have been prevented and the land maintained in fertile condition for a long period of years.

A large body of land, amounting to nearly 30,000 acres, contained from 1 to 3 per cent of alkali to a depth of 6 feet. The greater part of this class of alkali land is at present of no agricultural value except for the scanty pasturage it yields. Much of the alkali must be removed to make it available for crop production. In many locations, however, such land can be reclaimed and will then be found adapted to all classes of crops grown in the valley. More than 18,000 acres contained upward of 3 per cent of alkali, and on account of the heavy soils and low position it is to be doubted if

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such land can ever be profitably reclaimed. Conditions at the present time certainly do not warrant treating such soils when there are large areas of better land that can be made productive at a much less cost.

It was pointed out in the report by Gardner and Stewart that underdrainage was necessary not only to protect certain lands against injury from seepage waters and alkali, but also to reclaim lands already damaged; that the cost of underdrainage was slight in comparison to the value of alkali-free lands, and that money invested in drainage is in the nature of an insurance against loss of crops from seepage waters and alkali. Attention was also called to the fact that no serious engineering difficulties stand in the way of carrying out a comprehensive drainage system, that there is ample fall to the north and west toward the lake, and that the network of draws from 4 to 8 feet deep extending through much of the alkali land would furnish ready outlet for smaller drainage systems. It was further remarked that an area of nearly 100 square miles, which at present has but a mere nominal value, could be economically reclaimed, and that such work should appeal to the commercial spirit of the people and stimulate them to undertake this very desirable enterprise.

RECLAMATION OF THE SWAN TRACT.[a]

Several years after the publication of the Soil Survey report no important step had been undertaken toward any general scheme of reclaiming alkali lands. In 1902, therefore, the Bureau of Soils entered into cooperation with the Utah experiment station to demonstrate that alkali lands could be economically reclaimed. A tract of 40 acres was selected about 4 miles west of Salt Lake City, belonging to Mr. E. D. Swan. This tract is situated in sec. 5, T. 1 S., R. 1 N. The tract lies on the east of Williams Lake and has an elevation of about 8 feet above the bed of the lake. It was realized by all that if a tract of land of this character could be reclaimed there could be no possibility but that the reclamation of large bodies of land lying in this portion of the valley could be effected. The greater part of the tract was covered with a white crust of alkali and supported a scattering growth of greasewood (*Sarcobatus vermiculatus*). A railroad embankment crossed the tract from east to west, and city streets had been graded upon it many years before, when land speculation led many to believe that the city would rapidly extend its boundaries several miles to the westward of its present location.

[a] From 1902 to 1904 W. H. Heileman was in charge of the reclamation of the Swan tract.

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The surface soil consists of sandy and silty loam from 12 to 18 inches in depth. The underlying material varies from heavy loam to clay. In places a thin layer of sand occurs at a depth of 4 feet, while toward the lake, at an average depth of 26 inches, is found a white calcareous hardpan from 1 to 2 inches in thickness. Occasionally two layers of this hardpan are found, the first lying about 4 inches above the second. An alkali survey was made to determine the quantity of alkali contained in the soil to a depth of 4 feet. This showed that there was present in the soil to that depth from 2.5 to 5 per cent of alkali, consisting mainly of sodium chloride and sodium sulphate. Since 0.5 of 1 per cent of the alkali generally found in Salt Lake Valley represents about the upper limit of resistance of ordinary farm crops, it will be seen that the soil of the tract contained many times too much alkali for the growth of useful crops.

The following table contains analyses of representative samples of soil and subsoil taken from the Swan tract:

Chemical analysis of typical samples of soil from the Swan tract.

Constituent.	Sandy loam, 0–14 inches.	Loam, 14–30 inches.	Loam, 0–18 inches.	Clay loam, 18–42 inches.	Loam, 0–20 inches.	Clay loam, 20–40 inches.
	Per cent.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*
Soluble salt	1.64	1.34	2.43	2.60	2.46	2.28
Composition of soluble salt:						
Calcium (Ca)	1.22	1.04	.98	1.15	.81	1.05
Magnesium (Mg)	.48	.59	.49	.38	.48	.61
Sodium (Na)	30.77	29.51	32.79	33.24	31.61	33.26
Potassium (K)	4.39	4.76	3.62	3.07	3.64	2.80
Sulphuric acid (SO_4)	17.95	18.78	16.03	16.14	19.56	17.06
Chlorine (Cl)	34.33	29.36	39.27	41.02	36.66	39.40
Bicarbonic acid (HCO_3)	8.79	14.32	3.94	2.77	4.39	2.76
Carbonic acid (CO_3)	2.07	1.64	2.88	2.23	2.85	3.06

The ground water at this time (1902) stood at about 4 feet from the surface during the greater part of the irrigation season. In order to facilitate the removal of alkali salts by flooding, a drainage system was installed. The accompanying sketch map (fig. 2) shows the general plan of the drainage system and the size, depth, and interval between each lateral.

The average cost of the drainage system completed was $16.50 per acre. The system for the 40 acres includes 8 lateral drains and 1 main drain. Each of the laterals is 1,250 feet long and consists of 850 feet of 4-inch tile and 400 feet of 3-inch tile. The laterals were placed at intervals of 150 feet, except on the north side of the tract, where this distance was considerably increased to test the efficiency of drains at greater distances apart. The main drain across the west end of the tract consists of 520 feet of 6-inch tile, 300 feet of 8-inch tile, and 270 feet of 10-inch tile. The average depth of the drains over the entire tract was 4 feet. This was as deep as the system could be installed and secure a gravity outlet into Williams Lake.

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In order that the water used in flooding the tract might be measured a Cipoletti weir with recording register was installed at the point where the supply canal entered the tract. A registering weir was also placed at the outlet of the drainage system to measure the water that passed through the soil. From the outset the drainage system worked perfectly and proved adequate to discharge all water drained through the soil.

On account of the fall, graded streets, and railroad embankment, leveling the tract so that systematic flooding might be carried on proved a laborious undertaking. An attempt was made to get the land in shape for flooding before the close of the irrigating season of

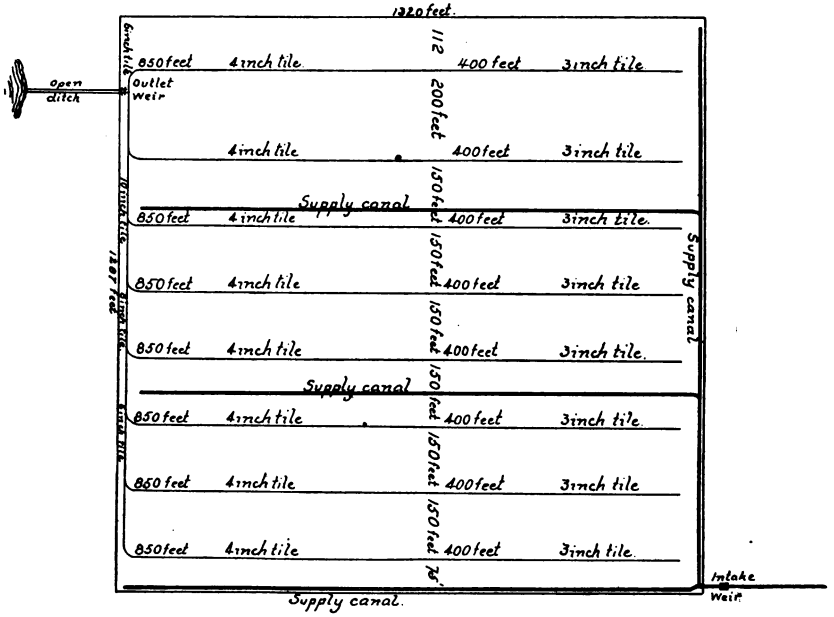

FIG. 2.—Plan of drainage system, Swan tract.

1902. A number of large checks were made inclosing a few acres each. Attempts to flood the tract, however, showed that more leveling was necessary to flood successfully the entire tract to a depth of several inches. This was done early in 1903, and flooding operations were continued during the greater part of the irrigation season. At the close of the season in 1903 a second alkali survey was made to determine the quantity of alkali removed by the flooding. This survey showed that large quantities of alkali had been removed, especially from the upper layers of soil. It was considered that the land was sufficiently sweetened to grow shallow-rooted crops. Accordingly in the spring of 1904 the tract was turned over to the Utah

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experiment station to conduct such crop tests. The entire tract was sowed during the latter part of May to wheat, oats, and barley. At this time the general tilth of the soil was not good on account of the flooding of the previous years. The soil somewhat resembles adobe, tends to bake or harden, and does not readily respond to cultivation. On account of the unfavorable physical condition of the soil the crop tests were not altogether satisfactory, but they plainly showed that the tract was already in condition for cultivation as far as the alkali content was concerned. Of the three crops the wheat made the best growth. Of the 40 acres planted about 15 per cent showed a thin stand where alkali still remained in the soil. The entire field headed short and showed the influences of late seeding. Early in August the greater part of the tract was plowed under to improve the physical condition of the soil. Flooding was then carried on for a period of several weeks, at the end of which time 10 acres were prepared and planted to winter wheat. By the spring of 1905 most of the wheat had made a good growth, but was thin and uneven in some places. The remaining 30 acres were planted to alfalfa and a variety of other crops, including potatoes, corn, berseem, beans, hemp, sugar beets, oats, barley, and spring wheat. There still remained some parts of the tract that had not been sufficiently leveled to secure the best results with irrigation, but in all parts of the tract, where water could be given the growing crops, results were very gratifying. No systematic flooding other than light irrigations was carried on during 1905. In 1906, 13 acres of the tract had a good stand of alfalfa, which had been planted the preceding season, and 4 acres were in winter wheat. The remainder of the tract was planted principally to alfalfa, using oats as a nurse crop. Other small portions of the tract were planted to crops requiring cultivation, such as corn, potatoes, and sugar beets. At the close of the irrigating season in 1906 the tract was practically turned over to the owner in a reclaimed condition. It is estimated that all excepting 1 or 2 acres of the tract contained so little alkali that no further damage from this source need be feared. A few small spots remained which still contained alkali in injurious amounts. These represent higher portions of the different checks which during the flooding operations had not been covered with water to a sufficient depth to leach out the alkali. The greater part of the tract is in alfalfa, and a very satisfactory stand has been secured. The fact that alfalfa can be successfully grown shows that the removal of the alkali has been very thorough, since it is well known that young alfalfa is one of the most sensitive crops to alkali.

At the beginning and close of each season an alkali survey has been made to determine the amount removed by flooding and the change in position of the alkali in the surface 4 feet of soil. The

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FIG. 1.—SWAN TRACT BEFORE RECLAMATION.

FIG. 2.—SWAN TRACT AFTER RECLAMATION, SHOWING HEAVY GROWTH OF ALFALFA.

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following table shows the quantity of alkali in the tract as shown by the surveys taken at different times:

Quantity of alkali in different depths of soil on certain dates.

Soil section.	Alkali in 40 acres.							
	September, 1902.		May, 1903.		October, 1903.		October, 1904.	
	Tons.	*Per cent.*	*Tons.*	*Per cent.*	*Tons.*	*Per cent.*	*Tons.*	*Per cent.*
First foot	1,363	20	499	14	101	8	38	4
Second foot	1,540	23	650	19	183	15	128	13
Third foot	1,766	27	1,066	31	330	28	212	24
Fourth foot	1,982	30	1,265	63	607	49	500	57
Total	6,651		3,480		1,221		878	

The alkali removed from the first foot between September, 1902, and October, 1904, was 97 per cent of the total quantity originally contained. From the second foot 91 per cent was removed, from the third foot 87 per cent, and from the fourth foot 75 per cent. These figures show that to a depth of 4 feet there has been 87 per cent of the original alkali removed from the entire tract.

Compared with its condition in September, 1902, the first foot of the tract contains only 3 per cent of the alkali originally carried, the second foot 9 per cent, the third foot 14 per cent, and the fourth foot 25 per cent. We find from this that the alkali has been removed most rapidly from the lower depths of the soil. It should be remembered that the alkali in the first 3 feet of soil had to pass through the fourth foot in its movement downward. The final elimination of alkali from the lower 2 feet of soil progresses more slowly than in the surface 2 feet. At the present time but little alkali remains in the first 2 feet of soil, and the elimination from the third and fourth should go on more rapidly.

The following table shows the volume of water added to the tract from September, 1902, until October, 1904. The table shows also the volume of drainage over the outlet weir, and the salts (alkali) removed from the tract in the drainage water. The results were obtained from continuous measurements and daily collections of water samples for the entire period.

Total quantity of water used in flooding the tract, quantity flowing off through drains, and quantity of salts removed in drainage water.

Month.	Volume of water added to tract.	Volume of drainage water from tract.	Salts in drainage water.
1902.	*Cubic feet.*	*Cubic feet*	*Pounds.*
September	284,400	158,700	152,200
October	940,000	265,000	195,100
November	[a] 171,300	251,000	353,800
December	[a] 166,500	139,700	187,800
1903.			
January	[a] 291,800	257,300	391,200
February	[a] 136,400	174,400	214,800
March	[a] 132,000	428,000	590,700

[a] Fell as rain or snow.

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Total quantity of water used in flooding the tract, quantity flowing off through drains, and quantity of salts removed in drainage water—Continued.

Month.	Volume of water added to tract.	Volume of drainage water from tract.	Salts in drainage water.
1903.	*Cubic feet.*	*Cubic feet.*	*Pounds.*
April	[a] 112,000	26,900	26,500
May	[a] 576,900 760,900	521,500	567,100
June	[a] 106,000 676,500	274,500	345,200
July	[a] 36,580 1,691,970	480,490	556,459
August	2,122,160	814,890	1,221,742
September	2,352,920	1,195,976	1,654,115
October	351,290	663,420	840,981
November	563,376	113,137	126,364
December	40,656	50,376	43,953
1904.			
January	217,800	26,396	18,912
February	299,112	382,628	475,631
March	187,308	390,114	521,974
April	255,552	258,519	382,335
May	382,974	60,903	61,466
June	[a] 44,970 618,172	68,132	31,487
July	[a] 87,120 1,610,807	430,459	385,364
August	[a] 35,820 1,920,726	774,285	711,021
September	[a] 20,320 802,153	579,215	579,215
Total	17,896,486	8,775,940	10,635,419

[a] Fell as rain or snow.

From the initial installation to October 1, 1904, we have the following:

Total volume of water added	cubic feet	17,896,486
	acre-feet	410
Total tonnage of salts removed	tons	5,317

The initial tonnage of alkali in this tract in September, 1902, by a careful alkali survey, was 6,651 tons. From the above record it would seem that about all the alkali had been leached from the tract to a depth of 4 feet. It should be remembered that this tonnage was obtained from little more than half of the water actually added to the tract. One factor, however, remains undetermined, viz, the volume of water lost by surface evaporation.

Certain phenomena enter into the work which tend to show that the salt removed from the tract will finally exceed the actual tonnage originally present. We find the reclamation from alkali is not limited to the 40 acres in question, but that the effect of this drainage system is far-reaching. Unmistakable evidences appear which show that the land lying contiguous to the tract has been most definitely benefited by drains installed on the 40 acres. Lands lying above this tract, which in years past have never produced crops, have during the past season yielded almost normally. The drains near

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these lands have carried from them their underground water and the alkali which it contained.

The following table shows the quantity and composition of the constituents removed in the drainage water at various times during the progress of the reclamation. The proportion of the different constituents is remarkably uniform and should remain so until some one or more of the salts is completely removed as pointed out by Cameron.[a]

Chemical analysis of drainage water from Swan tract.

[In parts per 100,000.]

Constituent.	Seepage water from tile drain before irrigating October 9, 1902.	Drainage water June 18, 1903.	Drainage water April 4, 1904.	Drainage water May 10, 1905.	Drainage water June 26, 1906.
Calcium (Ca)	4.5	7.2	6.1	3.7	3.7
Magnesium (Mg)	9.6	25.7	16.2	7.0	8.9
Sodium (Na)	696.6	1,177.1	726.2	366.0	392.4
Potassium (K)	31.9	26.0	26.9	10.8	12.6
Sulphuric acid (SO_4)	387.0	888.6	353.1	214.3	228.8
Chlorine (Cl)	765.0	1,207.0	888.1	395.8	431.2
Bicarbonic acid (HCO_3)	132.9	93.7	80.0	66.6	69.5
Carbonic acid (CO_3)	7.1	5.5	4.0	5.9	6.0
Total solids	2,034.6	3,430.8	2,100.6	1,070.1	1,153.1

The following table shows the increased acreage of soil containing a low percentage of alkali. The columns headed "September" show the original acreage, while the columns headed "October" show present acreage. The results of later surveys are not included in these tables, since it was found that the alkali conditions over the entire tract were but little changed:

Acreage of land of different grades of alkali September, 1902, and October, 1904.

Per cent alkali present in soil (grade).	First foot.		Second foot.		Third foot.		Fourth foot.		Total in 4 feet.	
	September, 1902.	October, 1904.	September, 1902.	October, 1904.	September, 1902.	October, 1904.	September, 1902.	October, 1904.	September, 1902.	October, 1904.
0.0–0.2	None.	38.8	None.	27.6	None.	17.0	None.	11.5	None.	23.7
0.2–0.4	3.0	None.	0.4	8.2	0.1	11.5	0.1	9.0	0.9	7.2
0.4–0.6	13.3	None.	2.3	3.2	.7	5.3	1.3	6.0	1.9	3.6
0.6–1	10.7	None.	8.0	None.	3.9	3.5	6.2	5.3	7.2	2.2
1–3	16.8	None.	19.7	None.	22.6	1.7	18.1	7.2	19.3	2.2
Over 3	5.0	None.	8.4	None.	11.5	None.	13.1	None.	9.5	None.

From the above brief description of the operations on the Swan tract it will be seen that excessive quantities of alkali can be removed from heavy soils by continuous flooding during a single irrigation season. The success of such an experiment can not but be far-reaching in its influence upon the alkali question in Salt Lake Valley.

[a] The Composition of the Drainage Waters of Some Alkali Tracts. Jour. Am. Chem. Soc., Vol. XXVIII, No. 10, 1906. See also Bul. No. 33, Bureau of Soils.

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It means that thousands of acres of land now lying idle can be made to produce profitable crops at a small outlay of time and money. While the present water supply is perhaps too limited to warrant the reclamation of all of the alkali areas, it is nevertheless adequate to reclaim a considerable proportion of the apparently worthless land.

METHODS USED IN RECLAIMING ALKALI LAND IN SALT LAKE VALLEY.

While there are abundant evidences that considerable land has been damaged by the accumulation of seepage water and rise of alkali, we must not lose sight of the fact that, since the earliest settlement in the valley, lands originally containing alkali have been reclaimed. Even at the present time the reclamation of alkali lands is progressing to a limited extent. That the question of alkali was considered serious by the settlers is brought out in some of the early writings. For instance, Charles Brough[a] states that "transformation of this sterile waste, glistening with beds of salts and soda and deadly alkali, seemed impossible." From this quotation it must not be inferred that any large bodies of land containing excessive quantities of alkali have ever been reclaimed. There are reasons to believe that, taking the valley as a whole, the quantity of alkali is decreasing, especially on the higher sloping lands which are better drained. Mention is made by some of the old settlers of the fact that in former times the year's supply of salt could be gathered from some one of the numerous small lake beds which occur in large numbers in the level valley between the Jordan River and the shores of Great Salt Lake. At the present time, while these ponds dry up during the summer season and crusts of alkali are formed on the surface, in no places can large quantities of salt be gathered by merely shoveling up the surface deposit. From this it may be inferred that as new tracts of land are being put under irrigation the alkali is gradually being driven into underground drainage channels and slowly working its way to Great Salt Lake.

The methods which are at present used in reclaiming alkali lands may be described under the heads of cultivation, washing, and flooding combined with drainage.

CULTIVATION.

Utilizing small tracts of land by thorough cultivation and planting crops is practiced not only in the Salt Lake Valley, but in many districts in the Pacific Coast States, especially by Chinese farmers and gardeners. A tract of land is selected usually of not more than a few acres, which on account of its alkali content is not considered

[a] Irrigation in Utah.

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valuable, and hence offers a cheap home site to the man of limited capital. By thorough cultivation the land is put in the best possible shape for crops, which are planted and make a successful growth. By spading or deeply plowing the soil the alkali accumulated at or near the surface is evenly distributed through the soil to the depth to which it is stirred. The soil is also made loose and porous, so that rains or applications of irrigation water tend to drive the alkali salts to a lower depth. The upper soil is then sufficiently reclaimed to permit the growth of crops which shade the surface, while repeated cultivation checks further rise of alkali. Each succeeding irrigation tends to drive the alkali deeper into the subsoil, until the greater part of it is carried away into the country drainage. Thus these small tracts of alkali land are made productive, frequently with no thought on the part of the owner that he is actually reclaiming the land. Could this method be adopted on a large scale or the land subdivided into a large number of small holdings and thoroughly cultivated, there is little doubt that large tracts of land in Salt Lake Valley could be made productive. Frequently in following out this method of reclaiming alkali soils large quantities of stable manure are worked into the soil, which tends to make the soil more open and allows the more ready percolation of rainfall and irrigation water. The addition of manure also serves as a stimulant to young crops, thereby enabling them to withstand whatever alkali may still remain in the upper layers of soil.

WASHING.

This is also a favorite method when an attempt is made to cultivate somewhat larger tracts of land than are mentioned in the above paragraph. Fields of 10 and 20 acres are selected which in their present condition are considered too strongly charged with alkali to grow crops. Sufficient leveling is done to get the land in shape for irrigation. When the land has been leveled so that all parts of the tract may be covered with water to a considerable depth, heavy irrigations are used during longer or shorter periods as required. In this way large quantities of alkali may be washed off the surface or driven to some depth in the soil. With the ground water at a depth of 4 or 5 feet from the surface the amount of alkali driven into a lower depth of soil with that removed from the surface by washing may sufficiently sweeten the land to permit growth of crops. Irrigation after the crop has become partially established is relied upon to further reduce the amount of alkali in the upper layers of soil. It is undoubtedly by this method that the early settlers reclaimed extensive areas on the east side of the valley. The slope in this portion of the valley is usually pronounced, and other conditions are favorable for removing the alkali originally contained in the soils. During the progress of the demonstration work on the Swan tract a small

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piece of land near by was reclaimed in this manner. Flooding was carried on at various times during the year, to be followed in the succeeding spring by a crop test. While this work was unsuccessful for the first two or three years and the crop returns did not pay for the cost of seeding, eventually this method was successful and the land now supports a fine stand of alfalfa. As late as the latter part of the summer of 1904 the surface was heavily incrusted with alkali salts. In 1905, the year in which the crop of alfalfa was established, a test of this soil was made to a depth of 3 feet in places where the stand of alfalfa was thin. It was believed that the alfalfa in these places was actually tolerating a high percentage of alkali. These tests showed that none of the soil to a depth of 3 feet contained sufficient alkali to injure alfalfa even in its younger stages. The ground water at this time stood within 3 feet of the surface.

Before attempting the reclamation of any considerable tract of land by this method it will be found advisable to determine accurately the depth of the ground water. As a general rule, if the ground water occurs within 3 feet or less, considerable difficulty will be found in leaching out large quantities of alkali by flushing or irrigation. If, however, the ground water is at a depth of 4 feet or more and the soil of open, sandy texture, washing, especially during the late summer season, will so reduce the quantity of alkali that crops may be grown the succeeding spring.

FLOODING COMBINED WITH DRAINAGE.

While no extensive attempts at reclaiming alkali lands have been undertaken by drainage combined with flooding, there are a number of interesting examples which deserve attention. In the vicinity of Granger, about 10 miles southwest of Salt Lake City, a number of farmers have successfully reclaimed land damaged by high ground water and accumulations of alkali. Some of the farmers who have undertaken this work are enthusiastic over the results, and each year continually increase the extent of their drainage systems. Drains consisting of ordinary drain tiles have been used in some cases, but equally good results have been obtained with drains made of boards. In some cases land originally covered each year by a heavy crust of alkali, with the water table near the surface, has been reclaimed in one year's time and now supports a heavy growth of alfalfa. While it has been realized by these farmers that the cost of installing the drainage system was considerable, they have been amply repaid by the increased growth of crops for the time and money expended.

Drainage systems with open ditches have also proved successful in a few instances. A greater part of the soils in the level portions of the valley stand well in bank and only require cleaning once or twice each year, so that this form of drainage system can be utilized by the farmer of limited means who can not afford to purchase tile.

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RECOMMENDATIONS FOR RECLAIMING ALKALI LANDS.

Before attempting the reclamation of any considerable tract of alkali land in Salt Lake Valley it is desirable for the farmer to consider the demonstration work on the Swan tract and other methods which have been used by the farmers of the valley. This work plainly shows that one of the most essential features is that the land must be placed in condition so that it can be entirely covered by irrigation water. Even with efficient drainage systems, if high spots remain in the fields which can only be covered to a very slight depth with water, these places will tend to hold and accumulate the alkali from the surrounding land. This does not necessarily imply that the land must be made perfectly level, but it must be so graded that an even flow of water across it may be had to secure uniform leaching. Where the land has only a slight fall it will be found desirable to divide the land into checks so that the water may be held on the land. It has been the experience of the Bureau of Soils on the Swan tract and elsewhere that the best results have been secured with a considerable depth of water. Light irrigations carry the alkali to a depth of a few inches, and when the soil dries off it readily returns to the surface, as previously explained. Flooding to a depth of 10 or 12 inches drives the alkali deeply into the soil, while succeeding floodings carry it still farther into the soil, thereby diminishing the chances for a second accumulation at the surface when conditions become favorable. It will be found desirable to plow the land to a good depth before each flooding in order that the water may more readily percolate the soil. On sandy soils that are open and porous plowing may not be necessary to effect a rapid downward movement of the water. Plowing the land at the close of the irrigating season will check evaporation and allow the soil to catch and hold any rain or snow that falls. Plowing in the fall is to be recommended for alkali land, no matter what method of reclamation is used to remove the salts.

The question of deciding whether or not drainage is necessary to reclaim a certain piece of land will depend on the quantity of alkali present, the character of the soil, and the depth to standing water. With porous sandy soils, only moderate quantities of alkali, and the ground water at a depth of 4 feet or more, heavy flooding for a few months will so reduce the alkali content that useful crops may be grown. To keep the land free from alkali heavy surface irrigation should be resorted to. This will drive down whatever salts are carried upward by the capillary rise of the soil moisture. At any time should the ground water rise within a few feet of the surface gradual accumulation of alkali may be expected. Should the practice of occasional heavy surface irrigations be discontinued alkali will undoubtedly increase in the upper layers of soil. Many examples

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have been recorded where land reclaimed in this way has again been ruined by a second accumulation of alkali. Such examples have probably prejudiced many farmers against freeing land from alkali by this means.

Where large quantities of alkali are contained in heavy clayey soils this method becomes of more doubtful application. The quantity of water necessary to wash the alkali to the point where it will no longer harm crops may be sufficient to raise the ground water, thereby defeating the object of the experiment. Again, the length of time involved in reclaiming such soils must be considered. While it may be possible eventually to reclaim heavy soils containing much alkali, the time necessary to do this will probably be so great that it will be far cheaper to drain the land to hasten the reclamation and put the land in crops. Frequently crop returns from productive land amount to from $20 to $50, and even more, an acre. From this it will be seen that it would be well worth from $15 to $20 an acre, the cost of a drainage system, if by this expense the farmer can get his land into paying crops one year sooner than he could by flooding alone. The question of the permanent reclamation also enters, for unless the land be naturally well drained and carefully managed alkali may accumulate in even greater quantities than were originally present.

DRAINAGE.

Aside from the ease and rapidity with which land may be reclaimed after a drainage system has been installed, there are several other reasons why drainage is to be recommended. In countries of abundant rainfall the good effects from drainage are appreciated and much land is drained where the removal of an excess of water is not absolutely necessary. The observant farmer has learned that drained land can be cultivated earlier in the spring and is warmer; that excess of rainfall is rapidly drained away, while sufficient moisture is retained in the soil to maintain a vigorous growth. In an arid region drainage will for these reasons add to the value of the soil aside from the question of removing alkali and seepage waters. Drainage may be accomplished by pumping plants that depend upon shallow ground water for their supply or by the use of gravity drains that will conduct the water to some natural outlet or to a sump dug for the purpose, from which it is raised. Either method is capable of lowering the ground water. If the drainage water does not contain soluble salts in large quantities, pumping may be used to furnish water for irrigation purposes. If, however, the drainage water contains too much salt to be applied to crops, it will be better to depend on a gravity system of drains. No great difficulty will be experienced in finding a gravity outlet in the Salt Lake Valley, as the land has ample fall and there is

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a network of narrow depressions that finally discharge into Great Salt Lake.

A drainage system to reclaim alkali land differs somewhat from the drainage systems commonly used in regions of abundant rainfall. To secure the best results the drains are placed at a greater depth and at a correspondingly increased distance apart. On the Swan tract, in heavy soils, drains placed 200 feet apart were apparently as successful as those placed 150 feet apart. On the light sandy loams where the alkali occurs in moderate quantity the drains may be placed at intervals as great as 250 and 300 feet. On the heavy clay soils with a large amount of alkali intervals of 150 feet between drains will be more satisfactory. Drains should be placed at least 3 feet deep, and depths of 4, and even 5, feet will repay the extra cost in laying them at this depth. The depth at which the drains are installed will be found to be about the depth to which the alkali can be leached from the soil. While 3 feet of alkali-free soil may be sufficient for most crops, underlying layers of soil containing alkali will be a possible source of danger, depending on the capillary power of the soil to lift the alkali to the surface. Each additional foot of soil that can be freed from alkali thereby decreases the chances of a second accumulation of alkali in the upper layers of soil. Four or 5 feet has been found to be a good depth to install drains, as most soils will accumulate little alkali when once it has been leached to this depth.

Open ditches are equally as effective as closed drains and have been extensively used in Egypt and other alkali districts in northern Africa.[a] Open ditches need frequent cleaning, occupy valuable space, must be bridged to transport farm machinery across fields, and frequently prove troublesome when flooding the land. For these reasons open ditches for small-field drains have not been extensively used in this country, although they are generally used for large-main drains that receive the surplus waters of many small drainage systems.

For closed drains tiles of burned clay or boxes of boards or planks may be used. Flat stones are frequently used for closed drains, as well as bundles of brush tied together and placed end to end. Since drain tiles have proved the most economical form of drainage implement, their use is generally to be recommended. For information in regard to laying tile and planning drainage systems the reader is referred to Farmers' Bulletin No. 187, entitled "Drainage of Farm Lands," and "Engineering for Land Drainage," by C. G. Elliott, of the Office of Experiment Stations. Tiles smaller than 4 inches have not given satisfaction in draining alkali lands on account of the difficulty in keeping them free from silt. The tiles should be crowded

[a] Reclamation of Alkali Lands in Egypt, by Thomas H. Means, Bul. 21, Bureau of Soils. 1903.

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closely together and silt catchment basins constructed in long lines of tile. It will generally be found advisable to construct these of sufficient size, so that the deposits of silt may be easily removed. Boxes made of boards or planks 4 or 5 feet long and 2 feet wide and at least 1 foot deeper than the tile have been found satisfactory. In Salt Lake Valley no unusual difficulty will be found in keeping the tiles free from silt, for the subsoils are usually heavy. After the tiles are laid care should be taken to settle the earth firmly over them. This may be done by filling to a depth of several inches and allowing a small stream of water to enter the trenches before filling in the entire trench. When once the earth is firmly settled over the lines of tile and it is found that silt does not enter the tiles, the land may be flooded over the lines of tile. If, however, much silt enters the tiles banks of earth or levees should be thrown up to protect the lines of tile. On the Swan tract little, if any, silt enters the tiles, and precautions necessary to keep the tiles open elsewhere were not considered.

After the drainage system is installed the land should be divided into checks so that flooding can be carried on. Flooding is necessary to hasten the final reclamation. Drainage may effectually check any further accumulation of alkali, but the alkali contained in the soil will not be removed until sufficient water is added to leach it downward through the soil. Heavy rains that penetrate the soil to the depth of the drains are valuable adjuncts to flooding, but in arid countries the ordinary rainfall can rarely be depended upon to remove the alkali entirely. A good depth of water even at infrequent intervals is more effective than frequent applications of a few inches of water, as explained elsewhere. More time will be necessary to leach alkali from stubborn clay soils than from sandy soils, through which the water readily percolates. On the Swan tract, with heavy soils and excessive alkali content, flooding for one season so reduced the alkali that shallow-rooted crops could be grown the following season. From this it would appear that, with an adequate drainage system and the land nicely leveled for flooding, the land should be occupied with profitable crops the succeeding year. In the case of heavy soils the growth of shallow-rooted annual crops is advised before planting a permanent crop, such as alfalfa. During the flooding operations the tilth of the soil may be destroyed and the cultivation and plowing under of stubble will help overcome the bad effects of water-logging the soil. Oats will be found a good crop to plant on newly reclaimed alkali lands. Oats withstand considerable alkali, make a rapid growth, and find a ready sale at good prices in Salt Lake City. This crop has also been found a good nurse crop for alfalfa when the latter is seeded. On the Swan tract alfalfa sown with oats as a nurse crop made fully as good growth as alfalfa without a nurse crop, and there was gained the crop of oats while the alfalfa was getting established the first year.

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It was observed that the flooding necessary to reclaim the land had not in any way impaired the productiveness of the soil, as the stand of alfalfa was pronounced as satisfactory as that secured on alkali-free soils in different parts of the State.

The cost of reclaiming alkali land in Salt Lake Valley will depend on the methods employed, the character of soil, and the quantity of alkali. With light sandy soils, little alkali, and deep ground water, cultivation and surface irrigation will be all that is necessary and the cost will be slight. The land must be prepared for surface irrigation, which will cost from $2 to upward of $30 an acre, depending on the character of the surface. There are large tracts of land in the valley where the amount of leveling will be small and the cost should not exceed $5 an acre. The cost of the cultivation and irrigation will also be low, so that $10 or $15 an acre will be sufficient to reclaim comparatively level sandy soils.

When a drainage system is necessary, as well as flooding for several months, the cost will be much greater. The drainage system on the Swan tract cost about $16.50 an acre and may be taken as an average cost of similar work in the valley. The cost of flooding for one year will vary from $5 to $10 an acre. By many it will be urged that the cost of leveling the land should not be included in the cost of reclaiming land, since all recognize that the land must be leveled before it can be successfully irrigated regardless of the presence of alkali. Deducting, then, the item of leveling, the cost of reclaiming alkali lands in Salt Lake Valley, even when drainage must be resorted to, will be from $20 to $35 an acre, surely a small outlay when the increased earning capacity of the soil is considered.

SUMMARY.

In previous pages it has been shown that extensive tracts of land in Salt Lake Valley west of the Jordan River are not productive on account of alkali. On account of the nearness to excellent markets it is highly desirable that the farmer should know how to remove the alkali. Reclaiming alkali land to a limited extent has been practiced since the first settlement in the valley in 1847, but no extensive work has been undertaken by private enterprise. An experiment on 40 acres of worthless alkali land 4 miles west of Salt Lake City, conducted by the Bureau of Soils and the Utah experiment station, showed that such work is practicable, since the reclaimed land now supports a good stand of alfalfa. These results were accomplished by heavily flooding the land after a drainage system had been installed. It was found that surface flooding for one year leached away large quantities of alkali from heavy soils; in fact the quantity of alkali was so reduced that shallow-rooted crops could be grown the following year. The cost of reclaiming this tract of land is not large in comparison to the

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enhanced value of the land. This experiment in reclaiming worthless alkali lands should prove an incentive to those seeking homes at moderate cost, or to men of larger capital interested in employing their means in safe investments. Much of the now idle land in Salt Lake Valley can be made to yield handsome returns by a limited outlay of time and money. Even those lands that, on account of the necessity of providing drainage systems, will require more effort to get rid of the alkali will be often found far cheaper than new lands now being developed in many parts of the West where market facilities and social and educational advantages are lacking and no definite information can be secured as to what crops may be successfully grown.

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U. S. DEPARTMENT OF AGRICULTURE,

BUREAU OF SOILS—BULLETIN No. 44.

MILTON WHITNEY, Chief.

RECLAMATION OF ALKALI SOILS AT BILLINGS, MONTANA.

BY

CLARENCE W. DORSEY.

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LETTER OF TRANSMITTAL.

U. S. DEPARTMENT OF AGRICULTURE,
BUREAU OF SOILS,
Washington, D. C., May 1, 1907.

SIR: I have the honor to transmit herewith a paper entitled Reclamation of Alkali Soils at Billings, Mont., by Clarence W. Dorsey, of this Bureau. This paper details the general conditions of this part of the Yellowstone Valley as regards alkali and seepage water, and gives an account of the reclamation demonstration carried on near Billings on the O'Donnell tract. The results of the work at Billings have been very gratifying and, I believe, have resulted in awakening general interest in the question of reclaiming these alkali lands, both by the farmers privately and in cooperation with the State.

I recommend the publication of this report as Bulletin No. 44 of the Bureau of Soils.

Very respectfully,

MILTON WHITNEY,
Chief of Bureau.

Hon. JAMES WILSON,
Secretary of Agriculture.

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RECLAMATION OF ALKALI SOILS AT BILLINGS, MONTANA.

INTRODUCTION.

Billings is situated in southeastern Montana, in a long, narrow valley characteristic of the lower Yellowstone River in the eastern part of the State. The valley is bounded on the north by sharp sandstone bluffs, rising from 200 to 500 feet above the valley floor. On the south in places bold bluffs of blue shale sharply define the valley or it merges into a mass of rounded hills that increase in height at greater distances from the river. The river occupies the lowest trough in the valley while successively higher terraces of low elevation give character to the surface relief of the valley. The terraces are marked by steep faces on the river side and extend as wide, level plateaus in places attaining a maximum width of 4 miles. They bear a definite relation to the course of the river and mark the various stages in the formation of the valley.

Billings has an elevation of 3,119 feet above sea level. The climate is characterized by extremes of heat and cold and an annual rainfall of about 15 inches, the greater part of which occurs during the spring and early summer months. The climate may be classed as typical of the great semiarid plains lying east of the Rocky Mountains.

At the time of the settlement of the valley only a very small proportion of the land showed any sign of alkali. The areas where alkali was plainly in evidence occurred in the eastern part of the valley and in occasional areas below the higher bench line. Near the present site of Billings and east to the river only alkali-resistant vegetation grew abundantly and there was sufficient alkali in places to form a crust. There were also other areas scattered throughout the valley that contained more or less alkali. With the construction of the Minnesota and Montana Improvement ditch in 1882 irrigation began, but the rapid settlement and development of the valley did not take place until 1890. About four years later, when large areas were under irrigation, damage from seepage water was first noticed. Some of the lower lands became too wet for cultivation and were given over to the growth of rushes and other water-loving plants. Other areas of water-logged soils appeared, increased

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in size, and were abandoned when cultivation was no longer possible. Not only were the lands damaged by the rise of the ground water, but alkali also appeared in increasing quantities and proved more serious than the injury from excess of water.

This damage continued for many years and the situation appeared serious indeed. Many farmers abandoned their farms and moved to other parts of the valley where cheap lands could be obtained. In the last few years, however, the situation has become more encouraging and conditions at the present time are such that the farmers of the valley need no longer fear alkali. It has been found that the alkali is confined to certain well-defined areas and is not extending beyond the boundaries of these areas, which do not aggregate more than 10 per cent of the area of the entire valley. An active interest in the subject of drainage has resulted in the formation of drainage districts, and already several large drainage systems have been completed, with others contemplated in the near future. Besides this important work the reclamation of a tract of alkali land by the Bureau of Soils has shown that it is comparatively easy to restore the damaged lands to their former productiveness by methods well within the reach of the progressive farmers of the valley.

SOIL AND ALKALI CONDITIONS IN THE VALLEY.

The alkali situation was first called to the attention of the Bureau of Soils in 1897. In that year Professor Whitney spent a few days in making a rapid reconnoissance of the valley. He found that there was much uncertainty on the part of the farmers as to just what the conditions in the soil were. It was then decided that a more thorough study of the valley should be made, to determine, if possible, the conditions in the soil, the possible results if present methods were continued, how to prevent the spread of alkali, and what should be done to reclaim the already abandoned lands. Such an investigation was made in the summer of 1898 by Mr. Thomas H. Means, and the results were published as Bulletin No. 14 of the Bureau of Soils.

RESULTS OF ALKALI STUDIES MADE DURING 1898.

Concerning the source of the alkali it was found that the farmers had advanced many theories and there was widespread belief that the alkali flats could probably be reclaimed by flooding the surface during a dry season and washing the crust off. Determinations of the amount and location of the alkali in the soil plainly showed that the crust contained only a small proportion of the alkali and that such a method would be inefficient. In every case of injury to crops that was examined it was shown that the first trouble was an accumulation of seepage water near the surface, and, while the water did not contain excessive quantities of alkali at first, continued evapora-

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tion resulted in concentrating sufficient alkali at the surface to injure crops.

An examination of the structure of the valley showed that it had been carved out of sandstones and underlying shales. The sandstones that rise abruptly above the valley on the north are porous and carry small quantities of magnesium and sodium sulphates, which frequently appear as a white incrustation on the bare rock surface. The soft blue shales forming the boundary of the valley on the south are penetrated by numerous fine cracks and joints filled with fibrous gypsum, while larger cavities carry gypsum and calcium carbonate. Throughout the mass of the shales are found large quantities of sodium and magnesium sulphates, which form a white incrustation on the surface.

The soils of the valley were found to have been formed from the weathering of these shales and sandstones, modified and deposited by stream action. So it would appear that the rocks are directly responsible for the soluble salts contained in the soils, these salts consisting principally of sodium and magnesium sulphate. The sandy soils occurring in the valley have been derived largely from the sandstones, and hence contain originally less salts than the heavy soils that have been derived from shales.

A detailed study was made of sec. 2, T. 1 S., R. 25 E., and maps were prepared showing the alkali and underground water conditions. These maps clearly showed the relation of seepage waters to the accumulation of alkali and how essential such a study is to the proper understanding of the question of providing remedies to check further damage. A study was also made of the quantity of salts being removed by a drainage ditch surrounding the town of Billings, which had been constructed to intercept the seepage waters from higher irrigated lands. From this it was found that the flow of water in the ditch was about 40 second-feet and that about 16½ tons of salt per hour was being removed; that is, it was rapidly carrying away the alkali seepage waters, thereby checking the concentration of alkali in adjoining lands.

The investigation further showed that before irrigation the salts were present, but so evenly distributed throughout the soils that they were not injurious to crops. The injury was found to be due to overirrigation, to the translocation and local accumulation of salts by seepage waters, to the imperfect drainage facilities in the clay soils, and the inability of the soils to remove the excess of salts and seepage waters. It was pointed out that the only way to prevent the final abandonment of the land containing alkali was to provide underdrainage systems to carry off the excess of water and the

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accumulated salts, but that the conditions in the valley were very simple, and that the rise of salts might be easily prevented.

RESULTS OF THE SOIL SURVEY OF THE BILLINGS AREA IN 1902.

During the summer of 1902 a more thorough study of the soil and alkali conditions of the Yellowstone Valley was made by Charles A. Jensen and N. P. Neill. The area surveyed extends from 1 mile west of Park City to a short distance east of Billings, in all nearly 25 miles. The valley has a maximum width of 7 miles about 8 miles west of Billings, but narrows in each direction from this point. The area surveyed comprises about 107 square miles (68,416 acres). The most extensive type of soil was found to be the Billings clay, with an area of slightly more than 17,000 acres. It is locally known as "gumbo," and is a dark-gray or black tenacious clay, often many feet deep and in such places practically impervious to water. When once the clay subsoil becomes filled with water drainage is exceedingly difficult. It has largely been derived from the Fort Benton shales that underlie the sandstones. Although it is difficult to cultivate, it produces good crops of timothy, blue stem, redtop, June grass, and other grasses, where the alkali content is low.

The Billings loam covers an area of more than 14,000 acres, and consists of about 12 inches of heavy loam overlying a light clay loam. It is also a dark-colored soil, but is easy to cultivate, and where there is little alkali is adapted to grain, vegetables, alfalfa, and other crops. Another extensive type of soil was found to be the Billings sandy loam, occupying an area of 13,568 acres. The top soil is a sandy loam to 12 inches overlying a light-yellow sandy loam which extends to a depth of several feet, and rests upon gravel, sand, or fragments of sandstone. This soil, unlike those just described, does not generally occupy the wide level terraces, but forms the gentle slopes of the foothills of the sandstone bluffs. It has been derived largely from the breaking down of the sandstones, has excellent underdrainage, and accumulations of alkali are rarely present. It is a rich, warm soil, well suited to any of the crops grown in the valley. Other types of soil are the Billings gravelly loam, a sandy loam mixed with waterworn gravel, and the Laurel sandy loam occurring along the river, where it frequently is made swampy by the seepage from higher lands.

The irrigation water supply for the valley is taken from the Yellowstone River and is ample for all purposes. The water is conveyed to different parts of the valley by gravity canals, some of which are many miles in length. The flow of water in the Yellowstone during the early summer months is large, at times the mean flow for May and June being upward of 10,000 second-feet. Since the water of the Yellowstone is principally derived from melting snow, the quality is excellent for irrigation. An analysis showed only 130

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parts of soluble matter per 1,000,000. Some irrigation is done with seepage water, usually with bad results on those soils already containing some alkali, since such water generally carries considerable salt in solution.

An examination of many samples of well, drainage, and spring waters showed all to contain soluble salts in quantity; well waters are especially bad, many containing from 1,700 to 9,000 parts per 1,000,000. Wells with the highest salt content are located in the level areas of Billings clay. Wells more free from salt are located on gravelly terraces, where the underdrainage is quite good. Springs along the river bank as a general rule are too salty for domestic purposes. The large quantity of salts found in the subsoil and drainage waters forcibly indicates the presence of accumulations of alkali in

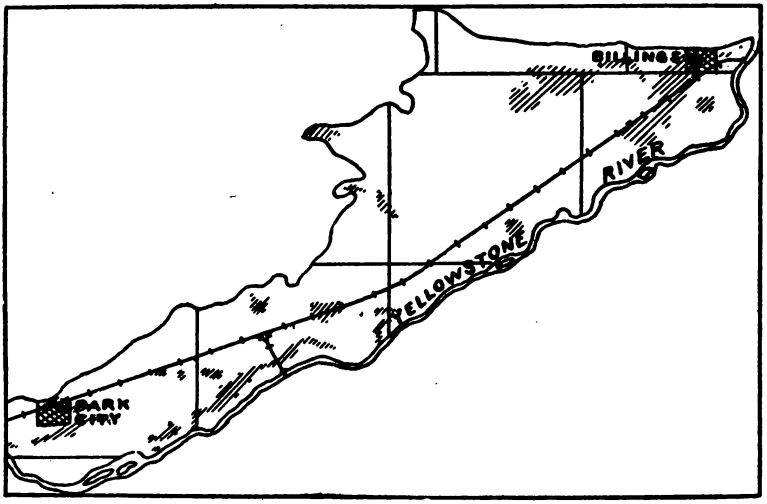

FIG. 1.—Map showing general distribution of alkali lands. Hatching shows affected areas.

the subsoil and insufficient underground drainage. The salts found in these underground waters consist mainly of sodium, magnesium, and calcium sulphate.

During the soil survey of 1902 a map was prepared showing the various grades of alkali land in the valley. In general it was found that the heavy clay and loam soils carried the most alkali. Alkali was not always found, however, in all of the clay areas, as some have a light subsoil and the underdrainage is good. The accompanying sketch map, prepared from the alkali map contained in the 1902 report, shows the extent and distribution of soils containing more than 0.60 per cent of alkali to a depth of 6 feet. It was found that of the area surveyed (68,416 acres) 42,944 acres contained less than 0.20 per cent (2,000 parts per 1,000,000) of alkali; that is, the quantity of alkali to a depth of 6 feet was so small that the effects on

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crops were negligible. Eighteen thousand six hundred and twenty-four acres contained from 0.20 to 0.60 per cent of alkali (2,000 to 6,000 parts per 1,000,000), and while the damage due to alkali was not great, in case all of the alkali became concentrated in the upper layers of soil injury would undoubtedly result. An area of 5,568 acres contained from 0.60 to 1.0 per cent of alkali, which is a little too much for the crops generally grown in the valley. Only 1,344 acres contained more than 1 per cent of alkali, and in their condition at that time (1902) were of little agricultural value. From these figures, representing the various grades of alkali, as well as from an inspection of the small sketch map, it will be seen that only about one-tenth of the area contains sufficient alkali to be a serious menace to crops.

In general it was found that the vertical distribution of the alkali is governed by the texture of the soil and subsoil and by the position of the soil and subsoil. In uncultivated areas of clay soil where alkali occurs its distribution below the first foot is quite uniform, the maximum quantity being found generally at a depth of 5 feet. Where the soils are heavy clay but have lighter subsoils the maximum alkali content is in one of the upper 3 feet of soil, but less alkali is found in the lower depths, the quantity depending largely upon the height of the ground water. In the deep clay soils where irrigation has been judiciously carried on the greatest quantity of alkali is found at a depth of from 3 to 6 feet. On some of the wide, level terraces and lower alkali lands along the river there is generally a surface accumulation of alkali with the maximum salt content in the first or second foot. In these localities the ground water is quite near the surface and within easy reach of the upward capillary power of the soil.

Above the canal in the sandy soils that have not as yet been irrigated little or no alkali was found in the soil to a depth of 6 feet, but moderate quantities were usually encountered at 7 and 8 feet, generally increasing with the depth. The alkali in the alluvial sandy loams found along the Yellowstone has resulted from evaporation of seepage water from higher lands. As before noted, the alkali in the higher bench and terrace soils has been derived directly from the breaking down of the sandstone and shale rocks, especially the latter, which are rich in soluble salts.

The general distribution of the larger alkali areas bears a direct relationship to the topography of the valley. As has been stated, the valley floor is marked by wide terraces, with a sharp bluff of from 15 to 30 feet emphasizing the line of demarcation between the different terraces. The outer or southern edge of these terraces is almost invariably higher than the central portion, and in places is even higher than the northern part. As a result of these topographic conditions, the depressions first became swampy as overirrigation was

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practiced on the higher soils. The irrigation water, as it slowly soaked through the soil, dissolved the salts and carried them to the troughlike depressions. Evaporation of much of this water concentrated the salts, and these swampy areas were finally abandoned as alkali flats. The poor underdrainage of the clay soils has materially hastened this process of converting water-logged lands into alkali swamps.

The following table contains analyses of samples of alkali crusts and soils. The samples are typical of the alkali found in the soils in the Yellowstone Valley. It will be noticed that sodium sulphate predominates, with much smaller quantities of calcium and magnesium sulphate. The chlorides and bicarbonates are present only in small amounts, with traces of alkaline carbonates.

Chemical analyses of salts of typical alkali crusts and soils of the Billings area.

Constituent.	6600. Near NW. corner sec. 2, T. 1 S., R. 26 E., alkali crust 0 to 1 inch.	6601. Center sec. 10, T. 1 S., R. 26 E., soil 0 to 10 inches.	6602. Center sec. 10, T. 1 S., R. 26 E., alkali crust 0 to 1 inch.	6603. S. center sec. 9, T. 1 S., R. 26 E., alkali crust 0 to 1 inch.	6604. Center sec. 8, T. 1 S., R. 26 E., crust 0 to 1 inch.	6605. W. center sec. 34, T. 1 S., R. 26 E., alkali crust 0 to 1 inch.
Ions:	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*
Calcium (Ca)	0.79	2.99	0.16	3.63	4.14	1.85
Magnesium (Mg)	1.79	.85	.24	2.01	2.57	2.95
Sodium (Na)	28.16	20.56	31.73	23.51	22.06	25.03
Potassium (K)	.72	9.63	.88	2.78	2.79	1.08
Sulphuric acid (SO_4)	67.73	45.85	59.93	62.98	61.06	66.49
Chlorine (Cl)	.33	Trace.	1.48	3.24	4.70	1.54
Bicarbonic acid (HCO_3)	.48	16.06	2.83	1.85	2.63	1.06
Carbonic acid (CO_3)	Trace.	4.06	2.75	.....	.....	.....
Conventional combinations:						
Calcium sulphate ($CaSO_4$)	2.71	10.07	.55	12.29	14.00	6.08
Magnesium sulphate ($MgSO_4$)	8.90	4.06	1.22	9.91	12.76	14.58
Sodium sulphate (Na_2SO_4)	85.57	35.12	85.06	66.66	55.68	72.93
Potassium sulphate (K_2SO_4)	1.60	21.41	1.96	6.18	6.15	2.41
Sodium bicarbonate ($NaHCO_3$)	.67	22.06	3.90	2.55	3.69	1.46
Sodium carbonate (Na_2CO_3)	Trace.	7.28	4.87	.....	.....	.....
Sodium chloride (NaCl)	.55	Trace.	2.44	5.41	7.72	2.54
Per cent soluble	44.68	.934	17.00	2.59	1.79	9.04

It is the exception to find in an arid country alkali consisting mainly of sodium sulphate; in most cases sodium chloride is the predominant constituent. As compared with the type of alkali found in other districts, the Billings type is generally supposed to be the least injurious to field crops. Some determinations as to its effects on crops were made in the different years during which the Bureau studied the alkali conditions in the valley, as well as in 1906, when the reclamation work was in progress. From the following statements it will be noticed that in general the crops are able to withstand more alkali than in areas where sodium chloride or the more toxic sodium carbonate prevails.

Although 1906 was the first year in which sugar beets were grown, it seems that they are the most resistant crop to alkali that is grown in

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the valley. Fields were found where the beets were growing in from 0.60 to 1 per cent of alkali, while the surface foot contained nearly 1 per cent. Alfalfa, after it has become well established, comes next in resistance, as it has been found in good condition in soil averaging a little over 0.60 per cent. In one place, where the water table was about 4 feet below the surface, alfalfa was in poor condition, with an average of 0.50 per cent of salt present. Oats have been found growing in soil containing 0.85 per cent and 0.91 per cent of alkali, as averages for 6 feet. The plants in both cases were small and weakly, and were only surviving. These limits are, of course, too high to be taken as a guide for the resistance of this crop, but shows how much salt can be tolerated by some individual plants. Good oats were found growing in soil with 0.58 per cent as an average for 6 feet and with no surface accumulation. Only one field of wheat was noticed where there were alkali spots. At the edge of these spots, where the wheat was dying, the soil averaged only 0.20 to 0.40 per cent to a depth of 6 feet, with 0.55 per cent for the surface foot.

A comparison of the conditions in selected areas in 1902 with the conditions existing in 1898 showed that the alkali accumulations were becoming more pronounced. This was particularly brought out by a study of sec. 2, T. 1 S., R. 25 E., which had been given special attention in 1898. By using the same method of alkali determination (the electrolytic bridge) it was found just what changes had taken place in the intervening period. In 1898, of the entire section (640 acres) only 186 acres contained alkali in what may be considered injurious quantities, while 454 acres contained some alkali, but not enough to damage crops. In 1902 it was found that the area of land containing much alkali had increased to 506 acres. Again, in 1898 it was found that the greatest concentration of alkali in the first foot of soil did not exceed 1 per cent, and there were only 13 acres containing from 0.60 to 1.0 per cent to a depth of 6 feet, but in 1902 there were 224 acres with from 0.60 to 1.0 per cent and 128 acres containing more than 1 per cent. This is a striking example of the manner in which alkali has continued to accumulate on a given tract of land where no remedial measures had been adopted. In 1906 the alkali conditions were studied again over the entire valley to ascertain the changes, if any, since 1902. It was found that the area affected by alkali had about reached its maximum limit; that is, the increase in land damaged by alkali was very slight in the four years that had elapsed since the survey was made in 1902. This study clearly brought out the fact, however, that the concentration of alkali in the well-defined alkali areas is increasing rapidly. Localities that in 1902 were only slightly damaged by alkali have since been abandoned because the land is no longer capable of producing crops. While this is a serious matter to those owning lands containing alkali, the

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knowledge that the possible limit of spread has been reached is gratifying for the entire valley.

RECLAMATION OF THE O'DONNELL TRACT.

In 1904 the Bureau undertook the reclamation of a tract of alkali land in the Yellowstone Valley. This was in line with the policy of the Bureau, namely, to establish demonstration experiments in reclaiming alkali land in different areas where a soil survey had clearly defined the alkali problem. The reports made by the Bureau in 1898, as well as in 1902, plainly showed the cause of the trouble and the way of attacking the question, and stated, moreover, that conditions in the valley were very simple as compared with other irrigated districts. In order, then, to demonstrate the principles in reclaiming alkali land, a tract of land 1 mile west of Billings was selected for the experiment. The tract was within easy reach of Billings and near one of the prominent roads of the valley, a location where the progress of the work could be observed by those interested. Pl. I, fig. 1, shows the condition of the land as it appeared when selected by the Bureau of Soils. No useful crops had ever been grown on the land, although one or two attempts had been made a score of years ago. There were many places covered with a thick crust of alkali, while other parts of the tract supported a scattering growth of greasewood, salt grass, and bunches of prickly pear cactus.

In texture the soil varies from a sandy loam to a stiff clay, locally known as gumbo. The clay soil is sticky and difficult to cultivate and so impervious that water percolates through it very slowly. In places at a depth of several feet gravel is found, which is often firmly cemented together and is well-nigh impervious to water. An alkali survey of the tract gave the following results: Fourteen acres, nearly three-fourths of the tract, contained more than 1 per cent of alkali to a depth of 4 feet; 4.2 acres contained from 0.60 to 1.0 per cent, and 1.6 acres carried from 0.40 to 0.60 per cent of alkali. The maximum alkali content was found in the first foot and usually decreased downward. Where the soil consisted of heavy clay the greatest amount of alkali was found. The alkali was typical of that found in other parts of the Billings area. It consisted mainly of sodium sulphate, with smaller quantities of magnesium and calcium sulphate, traces of chlorides, and bicarbonates, but no traces of carbonates. The ground water in midsummer stood within 4 or 5 feet from the surface and carried over 2 per cent of soluble salts.

On account of the large quantities of alkali present and the slow movement of water through the soil a drainage system was considered necessary to achieve marked results within a reasonable time. An outlet was easily secured by digging 660 feet to the drainage

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ditch that surrounds the city of Billings. The question of securing tiles for the drainage system proved more troublesome. When it was found that no tiles could be purchased near at hand, an effort was made to interest a local brick company in manufacturing tiles. This resulted in the purchase of a tile machine and the contract was awarded to this company. There had always been a small demand at Billings and near-by points for drain tiles and it was believed a much larger demand could be created if the tiles could be sold at much lower prices than those purchased at distant points. By mixing weathered shale with the ordinary brick clay it was found that a satisfactory tile could be made. After making several hundred feet of tiles the tile machine was broken and no further effort was made by the brick company to fulfill their contract. The Bureau was then forced to purchase tiles from Kansas City, Mo., which greatly delayed the installation of the drainage system. The accompanying

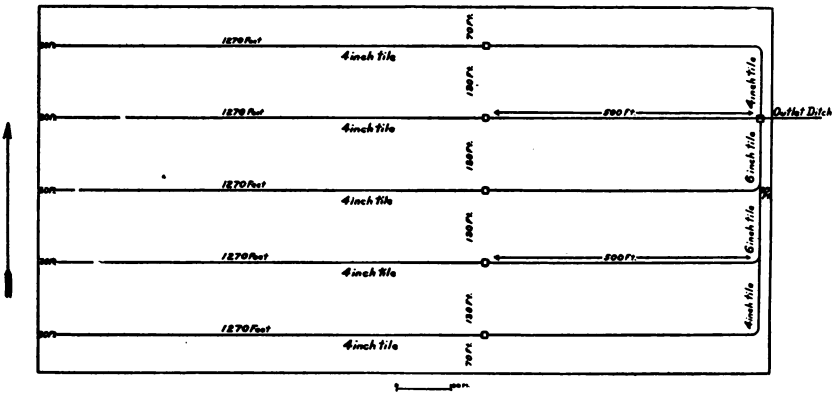

FIG. 2.—Plan of drains, O'Donnell tract.

sketch map shows the general plan of the drainage system on the O'Donnell tract. The drains were placed at an average depth of 4 feet. The fall given the lines of tile was about 3 inches in 100 feet. The slope of the land is to the north and east. On account of the heavy clay subsoil underlying most of the tract, the drains were placed at intervals of 130 feet. The five laterals consist of 4-inch tiles, with silt catchment basins placed 500 feet from the eastern end of each lateral. From the junction of the laterals the outlet drain consists of a box open on the bottom placed at an average depth of 5 feet. Registering weirs were placed at the outlet of the drainage system and at the point where the water-supply canal enters the western end of the tract.

The cost of installing the drainage system was approximately $35 an acre. This excessive cost was occasioned by the cost of the tiles purchased at a distant point and by the dry compacted clay soils,

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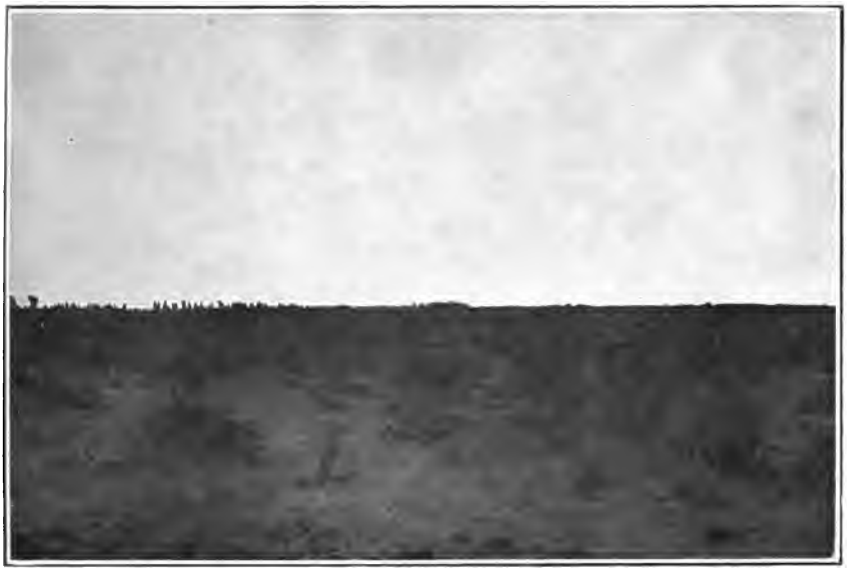

FIG. 1.—SHOWING BARREN ASPECT OF THE LAND INCLUDED IN THE O'DONNELL TRACT BEFORE RECLAMATION.

FIG. 2.—SHOWING HEAVY STAND OF OATS ON THE SAME TRACT AFTER ONE YEAR'S TREATMENT BY THE UNDERDRAINAGE-FLOODING METHOD OF RECLAIMING ALKALI LANDS.

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which made digging the ditches painfully slow. It is believed that with tiles sold by local factories at reasonable prices and by excavating the trenches, in the spring, when there is more moisture in the soil, the cost of drainage for most of the Billings area will not exceed on an average $15 to $20 an acre. The drainage system was completed too late in the season of 1904 to carry on flooding. The tract, however, was carefully leveled and checks thrown up to hold the water on the land. Fall plowing was also resorted to in order to leave the soil in an open and loose condition so that winter rains and snow might readily enter.

The early spring of 1905 was remarkable for the exceptionally heavy rainfall. It undoubtedly played an active part in effecting the reclamation of the O'Donnell tract. With the beginning of the heavy and continued rains the drains at once responded and by the latter part of June the abnormal rainfall had materially reduced the alkali content of the tract. From early in July until the end of September the tract was submerged practically all of the time. By an adjustment of small supply canals the water was allowed to run night and day and the checks were continually filled. There were two short periods when there was a scarcity of water and the tract was not flooded, but these were not long enough to allow the alkali to accumulate at the surface.

At the end of September, 1905, the soil was allowed to dry and an examination was made to determine the changes that had taken place in alkali content of the tract. It was found that there still remained in the soil only about one-seventh of the alkali that was originally present. An alkali survey made in June, 1905, after the heavy spring rains showed that the maximum alkali content was in the second and third feet, but at the close of the flooding operations in September the maximum was almost uniformly in the fourth foot. During the flooding period sufficient water was used to cover the entire tract to a depth of 6 feet, while the rainfall during this same period was only 1.37 inches; the evaporation was estimated at 12 inches from a free water surface. About one-half of the water used in flooding passed over the outlet weir at the point where the outlet ditch empties into the Billings drainage ditch, 660 feet east of the reclamation tract. A large part of the water undoubtedly passed into the country drainage of the tract or along the line of the outlet ditch. Tests of the drainage water made during the flooding season showed that the soluble salts decreased from 9,000 parts to 3,250 parts per 1,000,000. At the close of the season the tract was plowed and harrowed to overcome as far as possible the bad effects of the continued flooding.

Early in the spring of 1906 the soil appeared to be in excellent

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condition. The surface indications showed no traces of alkali, except along the north side of the tract, where no flooding had been carried on. An alkali survey showed even less alkali than had been found in September of 1905. In May the soil was disked and harrowed preparatory to seeding oats. The soil responded nicely to this treatment and an excellent seed bed was obtained. Russian side oats were planted May 16 and made rapid growth. A heavy stand was secured that compared favorably with crops sown on alkali-free soils in various parts of the valley. Severe wind and rain storms, however, considerably damaged the crop at the ripening period. The crop was harvested the last of August. Pl. I, fig. 2, shows the appearance of the tract a few days before the crop was cut. The yield was 44 bushels an acre, making the return for the 15 acres amount to $260. Considering that no crops had ever been grown on this land, the results obtained the first year after flooding were very gratifying. They showed conclusively that the removal of alkali had been most thorough and that the land was now in condition to grow any crop adapted to the climatic conditions of the valley.

At the time the crop was removed the tract was returned to the owners. It was the original intention to leave the reclaimed land with a satisfactory stand of alfalfa upon it, but the rapid extension of Billings made the land highly desirable for building purposes. The owners therefore subdivided the tract and sold it for residence purposes, except two lots which were reserved for vegetable gardens.

PRIVATE EFFORT IN RECLAIMING ALKALI LAND.

Prior to 1904, the year in which the Bureau undertook the reclamation of the O'Donnell tract, but little effort was made either to reclaim alkali lands or to utilize them in any way. Generally when the land accumulated sufficient alkali it was abandoned to salt grass and greasewood and valued only for the scant pasturage it afforded. Even during the period when the area of alkali was fast increasing, the farmers, while deploring the injury to their lands, seemed unable to adopt any preventive measures. Many whose lands were ruined moved elsewhere and took up new land, as they could easily do while prices remained low. A few farmers, it is true, tried to cultivate those portions of their farms damaged by alkali by plowing in the fall and seeding to oats the following spring. But the invariable result was that the land did not produce enough grain to pay for cutting and thrashing.

Some few farmers dug shallow ditches to remove the seepage water and some of the alkali, but the ditches were not deep enough and were soon allowed to fill up again, so that no beneficial results were accomplished. Within the last two years, however, considerable progress has been made in taking means to remove alkali from the

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lands or to prevent conditions from becoming worse. In the summer of 1905 two drainage systems were installed. A bill has also been passed providing for the formation of drainage districts and county officers to look after such matters. By the enactment of this law it is possible for persons owning damaged lands to unite and constructs drains with outlets. Before the passage of this law it was not always possible to do this, as there was no way of securing an outlet through another man's land unless the owner gave his consent. As a result of this law one large district was completed and active steps were taken to form others. In addition to these districts formed under the provisions of the State law, considerable work is being done by groups of farmers cooperating to improve their land. On account of the interest manifested on every side by the farmers in the subject of drainage the prospects are very bright in the Billings area.

With the definite knowledge that alkali is not rapidly encroaching on new good soils and with the question of drainage for the largest areas affected by seepage water and alkali attended to, it now remains for the individual farmer to free his own particular land from alkali. This will require considerable effort, for some tracts of alkali land included at the present time within the drainage districts are situated long distances from the main drains. In a region of sandy subsoils and good underdrainage reclaiming alkali soils may be accomplished with but little effort, but it is unreasonable to suppose that heavy clay soils can be freed from excess of water and alkali by a deep main drain fully one-half mile away. This was clearly proved by the history of the O'Donnell tract reclaimed by this Bureau. The eastern end of this tract was only 660 feet from a deep ditch which had been dug prior to 1898, yet in 1904 this part of the tract contained the greatest quantity of alkali. From this it may be inferred that while the drainage ditch removed the excess of water from this part of the tract and perhaps checked the further accumulation of alkali it did not remove alkali from the upper layers of soil. This was not accomplished until a drainage system had been installed and copious flooding resorted to for several months. And so in many parts of the valley, after the district drainage systems have been constructed, in order to remove any considerable quantity of alkali it will be necessary to provide drainage for individual tracts of land. On the heavy soils having clay subsoils to a depth of several feet it will be advisable to place the drains at a good depth, say 4 or 5 feet, at intervals of about 150 feet apart. After this work has been completed the land should be flooded until it is believed shallow-rooted crops can be grown. For the small field drains tiles may be used in case they can be secured at reasonable prices, or boxes made of boards or planks, or, in case these prove

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expensive, open ditches will prove effective if cleaned as often as may be necessary.

From the experience of the Bureau on the O'Donnell reclamation tract even the heaviest clay soils of the valley may be freed from alkali by flooding during the irrigating season, after an efficient drainage system has been installed. When the soils contain only moderate quantities of alkali in the areas where drainage districts have been found drainage of individual fields may not be necessary. If some crop that will tolerate some alkali, such as sugar beets, can be started and the soil has fair subsoil drainage each irrigation will remove a certain proportion of the salts, and eventually the field will be entirely reclaimed. Undoubtedly there are many areas in the drainage districts where the conditions of alkali and subsoil drainage are such that the land can be reclaimed in this manner. Deep plowing of the soil and liberal applications of water will materially hasten the reclamation of such tracts, as well as any course of treatment that will check surface evaporation and allow the ready percolation of water through the soil.

SUMMARY.

The soils of the Yellowstone Valley, in which Billings is situated, are mostly heavy loams and clays, which in their natural state contained large quantities of salts, especially in the lower depths. The origin of these salts is in the shales and sandstones, which upon weathering have formed the soils of the valley.

In the early development of the valley the areas visibly affected by alkali accumulations were small and attracted little attention. With extensive irrigation certain tracts of land became wet and swampy, gradually accumulated alkali, and finally were abandoned.

This damage from seepage water and alkali was clearly the result of overirrigation on heavy soils having very poor natural drainage. For a number of years the area of damaged lands spread rapidly, and conditions were considered serious by the farmers of the valley, and many moved to other places rather than combat such unusual and formidable problems.

An examination in 1898 by the Bureau of Soils showed that the deep subsoils were rich in salts, that shallow drains would be ineffectual, and that washing the surface only removed the accumulated alkali from a shallow depth of soil. It was pointed out that underdrainage to be effective must be deep, and that irrigation water should be sparingly used to prevent ruining lands at lower levels. Subsequent studies of the soil and alkali conditions of the valley in 1902 more clearly defined the problems and showed that the area of damaged lands was yearly increasing, and that it was imperative

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for the farmers to adopt measures to prevent widespread injury to some of the finest tracts of land in the valley.

The experiment in reclaiming a worthless tract of alkali land by deep underdrainage and surface flooding, conducted by the Bureau of Soils, proved successful, and after one year's treatment a good crop of oats was harvested. This work showed the farmers just what steps were necessary to reclaim damaged lands and undoubtedly helped to arouse an interest in the subject.

At the present time the outlook in the valley is most promising, owing to the widespread interest manifested in the formation of drainage districts in the areas most severely damaged by excess of seepage waters and alkali. The State drainage laws make it possible for farmers to construct large drainage systems, and such work is progressing rapidly, while groups of farmers are closely cooperating to the same end.

With the subject of regional drainage so adequately provided for, the reclamation of small farms or individual fields will follow as soon as the farmers appreciate the necessity of further effort in addition to the larger remedial measures that have been adopted. In some cases this will consist of the thorough drainage of fields, using the main drains as an outlet and leaching the alkali from the soil by surface flooding. In other cases careful cultivation and irrigation of crops not especially sensitive may be depended upon to remove the small amount of salt contained in the soil.

In whatever way the alkali soils may be finally reclaimed, the people of the valley are certainly to be congratulated upon their commendable enterprise in so promptly undertaking measures to check the ravages of seepage water and alkali. It is an excellent example and one that should be followed by many other districts in various parts of the West.

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Issued September 9, 1907.

U. S. DEPARTMENT OF AGRICULTURE,

BUREAU OF SOILS—BULLETIN No. 45.

MILTON WHITNEY, Chief.

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THE MOISTURE EQUIVALENTS OF SOILS.

BY

LYMAN J. BRIGGS AND JOHN W. McLANE.

WASHINGTON:
GOVERNMENT PRINTING OFFICE.
1907.

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LETTER OF TRANSMITTAL.

U. S. DEPARTMENT OF AGRICULTURE,
BUREAU OF SOILS,
Washington, D. C., May 8, 1907.

SIR: I respectfully transmit herewith a technical report, entitled "The Moisture Equivalents of Soils," prepared by Messrs. Lyman J. Briggs and John W. McLane, formerly of the Physical Laboratory of this Bureau. This paper covers work done during their connection with this office, and I recommend that it be published as Bulletin No. 45 of the Bureau of Soils.

Respectfully,

MILTON WHITNEY,
Chief of Bureau.

Hon. JAMES WILSON,
Secretary of Agriculture.

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THE MOISTURE EQUIVALENTS OF SOILS.

INTRODUCTION.

It is important in the comparative study of soils that the mechanical composition, which forms the basis of most comparisons of this kind, shall be supplemented by the quantitative measurement of other characteristics, such as the moisture retentivity and the rate of capillary movement of water under standard conditions.

The measurement of the water-holding capacity under the action of gravity does not furnish a satisfactory method for comparing soils in a quantitative way, as such determinations are dependent upon the percentage of interstitial space in the soil, which in its turn depends upon the way in which the soil has been manipulated. It occurred to the authors that a satisfactory basis of comparison might, however, be established by determining the amount of water which different soils are capable of retaining when the moisture in the soil is subjected to a constant measured force, *sufficient in magnitude to remove the water held in the larger capillary spaces.* This may be easily done by placing the moist soils in suitable perforated cups and subjecting the soil moisture to centrifugal force. The magnitude of the force employed can be readily calculated by determining the radius of rotation and the speed.

MOISTURE EQUIVALENTS.

The percentage of water retained by a soil, when the moisture content is reduced by means of a constant centrifugal force until it is brought into a state of capillary equilibrium with the applied force, we propose to designate by the term *moisture equivalent.* In a series of samples in which the moist soils are all in equilibrium with the same force, it logically follows that if these soils are placed in contact, each soil containing an amount of water equal to its moisture equivalent and the packing of each soil being the same as in the centrifugal machine, the soils will be in capillary equilibrium and no movement of water from one soil to another will take place. This conclusion has been verified experimentally. The packing to which each soil

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is subjected in the centrifugal machine seems as nearly definite and reproducible as it is possible to obtain, since each element of mass at the same distance from the axis is subjected to the same centrifugal force. When a layer of soil of uniform thickness is employed, the conditions are practically the same for each soil examined. Consequently the determination of the moisture equivalents of a series of soils shows the amount of moisture each will retain when all are packed in a uniform manner and are subjected to the same centrifugal force.

DESCRIPTION OF CENTRIFUGAL MACHINE USED FOR DETERMINING MOISTURE EQUIVALENTS.

In designing apparatus for the determination of the moisture equivalents of soils the first requisite is a shaft with bearings capable of standing high shaft velocities without undue heating. To save expense various commercial machines were considered with a view to their adaptation to this purpose, and a grinding machine was finally secured as most nearly fulfilling the desired condition. The bearings did not, however, prove satisfactory, and it was only after special bronze bearings had been substituted and the shaft had been carefully ground that a speed of 5,000 revolutions per minute could be maintained without unsafe heating. The steam turbine, with the centrifugal apparatus mounted on, or directly connected to, the turbine shaft, is the ideal arrangement for high-speed machines of this class.

The machine as finally used is shown in Plate I, fig. 1, with the centrifugal head in position. The main shaft passes through the cylindrical head, which is secured in position by being clamped between two heavy flanges by means of a nut threaded on the shaft. The other end of the shaft was designed to take a centrifugal head of another form.[a] In the illustration, however, this end of the shaft simply carries a small worm which engages a gear wheel having 100 teeth. A small spur on the side of the gear wheel momentarily closes a circuit once each revolution, actuating a sounder in the engine room, and in this way the speed of the machine could be determined and kept nearly uniform by regulating the speed of the engine.

The construction of the centrifugal head is shown in Plate I, fig. 2.

[a] Such a machine is capable of serving a double purpose, since with another form of centrifugal head it can be used as a means of extracting and collecting from a moist soil a portion of its soil solution. The composition and concentration of the solution thus removed would appear to be identical with that in the soil from which the plant derives its mineral food, and the method seems a promising one for investigating the relation of the composition and concentration of the water-soluble constituents to the productivity of the soil.

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The cylinder, which is of brass, is 24.7 cm. outside diameter, and the thickness of the cylindrical wall is 1.3 cm. Care was taken to secure a uniform, homogeneous casting, and both the cylinder and cover were accurately finished inside and out, which gave a perfectly balanced system. The cylinder carries in its interior eight brass cylindrical cups with fine gauze bottoms covered with thin disks of filter paper, in which the soils under investigation are placed. Each of these cups rests upon the flat surface of a cylindrical segment fitted to the inside of the centrifugal head. These segments are equally spaced about the interior of the cylinder and are held in position by screws. To keep the cups in position when the machine is at rest a brass diaphragm having apertures for each cup is fitted into the cylinder, as shown in the illustration. The cover is provided with a slightly tapered flange which fits snugly over the open end of the centrifugal head. The moisture removed from the samples works out through the joint between the head and the cover. Since the whole outer surface of the cylinder is accurately turned and smoothly finished, the air friction is reduced to a minimum.

While it is possible to examine eight samples of soil at one time with the machine as described, this procedure is apt to throw the machine out of balance, for the samples will in general lose different amounts of water during the test. Since duplicate determinations were desirable, four samples were run at one time. The cups containing the same sample were brought to equal weight and placed on diametrically opposite sides of the cylinder, which kept the machine in balance throughout the experiment.

This machine was normally driven at 5,000 revolutions per minute by means of a steam engine running at 300 revolutions. A belt from the fly wheel of the engine drove a shaft, to which the centrifugal machine was belted, at 2,000 revolutions per minute. The centrifugal machine and the pillow blocks carrying the end of the shaft opposite the machine were mounted on the same cement foundation, which rested upon a bed of sand and was free from the floor and walls of the building. This effectually prevented the machine from producing any serious vibration or jarring of the building.

It is an essential condition in the successful operation of all high-speed centrifugal machinery that the rotating system shall be as nearly perfectly balanced as possible. Machines which are not in perfect balance vibrate badly when the period of rotation corresponds to the natural period of vibration of the machine. This speed is sometimes spoken of by manufacturers of centrifugal apparatus as the "critical speed," above or below which the machine operates much more quietly.

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The centrifugal force f,[a] expressed in dynes, acting on an element of water, dm, is

$$f = 4\,\pi^2\,n^2\,r.\,dm$$

where n is the number of revolutions of the apparatus per second and r is the distance of the element of water from the axis. Since the bottoms of diametrically opposite cups, when in position in the cylinder, were 21.5 cm. apart, we would have for a layer of soil 5 mm. in thickness, a mean radius of rotation of 10.5 cm. The centrifugal acceleration, i. e., the force acting on unit mass of water, corresponding to each of the different velocities employed in the following experiments, is given below (Table I). We can also express the centrifugal accelerations in terms of the acceleration of gravity as a unit, since the acceleration of gravity is equal to 980 dynes. To avoid confusion, the calculations in the table are given in terms of unit volume (1 cubic centimeter) of soil moisture, which is assumed to have unit mass. The second column gives the force in dynes, and the third column gives the force in terms of the force of gravity as a unit.

TABLE I.—*Centrifugal force acting on unit mass of soil moisture at the various speeds employed.*

Revolutions per minute.	Force, dynes per c. c.	Force, grams per c. c.
2,700	839×10^3	857
3,000	1,036	1,057
3,200	1,179	1,203
4,100	1,936	1,975
4,200	2,031	2,073
4,300	2,129	2,174
5,000	2,878	2,937
5,500	3,483	3,554

EFFECT OF DURATION OF TEST ON THE MOISTURE EQUIVALENT.

In order to determine the time required to bring the moisture content of the samples into capillary equilibrium with the centrifugal force applied, a series of preliminary experiments (varying in duration from 15 to 60 minutes) was made upon several soil types. The results are given in Table II. The first column of the table gives the

[a] Some English writers object to the term "centrifugal force." The term has, however, so thoroughly established itself in this country and is so generally understood that it appears advisable to use it here. There is, of course, no actual force exerted in a centrifugal machine which tends to pull the water out of the soil. What actually occurs in the machine is just the opposite; that is to say, the soil is pulled away from the water. There is an acceleration of the soil directed inward toward the axis, which leaves the water behind. The result is, of course, the same as if the water were subject to an equal acceleration outward.

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type of soil used, the second column gives the percentage of moisture remaining in the soil at the end of the test, and the third column gives the time during which the moisture in the sample was subjected to centrifugal force. It will be noted that there is a slight reduction in the moisture equivalent as the time increases in nearly every case, although this effect is small after a period of thirty minutes.

These determinations were made upon a thicker layer of soil than was employed in the final experiments, so a somewhat longer time was necessary to attain approximate equilibrium. Thirty minutes was accordingly decided upon for the duration of the tests in the final experiments. In some extremely heavy soils the moisture content might be slightly reduced by extending this period, since the distribution of moisture in a sample would probably reach a state of complete equilibrium only after a considerable interval had elapsed. Errors due to other causes, however, such as the fluctuation in the speed of the machine, did not appear to us to justify an attempt for further accuracy in this direction.

TABLE II.—*Effect of duration of test upon moisture equivalent.*

Soil type.	Moisture after test.	Duration of test.	Speed per minute.	Soil type.	Moisture after test.	Duration of test.	Speed per minute.
	Per cent.	*Minutes.*	*Revs.*		*Per cent.*	*Minutes.*	*Revs.*
Leonardtown loam.	14.9	15	4,800	9248 Hagerstown loam	17.3	30	5,000
	14.6	15	4,800		17.2	45	5,000
	13.7	30	4,800		16.2	45	5,000
	13.1	30	4,800				
	13.3	45	4,800	9037 Hagerstown clay	22.2	30	5,000
	13.4	45	4,800		21.9	30	5,000
	13.0	60	4,800		21.7	45	5,000
	12.4	60	4,800		21.4	45	5,000
10212 Hagerstown silt loam	16.0	30	5,000	8589 Norfolk fine sand	3.1	30	5,000
	15.7	30	5,000		3.4	30	5,000
	15.5	45	5,000		3.1	45	5,000
	15.2	45	5,000		3.3	45	5,000
9248 Hagerstown loam	17.2	30	5,000				

EFFECT OF INITIAL WATER CONTENT ON THE MOISTURE EQUIVALENT.

A second series of experiments was made to determine whether the percentage of water used in moistening a soil had any influence upon the moisture equivalent, providing, of course, that the amount of water used was always greater than the soil could retain at the speed employed. It was thought that perhaps something akin to puddling might take place when relatively large amounts of water were used. Experiments were made with several different moisture contents in the case of each soil examined. One sample of each soil was saturated and another was puddled as much as possible by thorough mixing so as to accentuate the influence of the preliminary treatment of the soil upon the moisture equivalent. It will be noted from a comparison of the results, which are given in Table III,

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that the initial moisture content in the case of the Leonardtown loam had very little influence upon the per cent of moisture remaining after the test. The same is true of the subsoil of the Norfolk sand. In the case of the subsoil of the Cecil clay, which is a heavy soil, the results show a gradual increase in the value of the moisture equivalent as the initial water content is increased, and the effect of puddling in this soil is marked, the percentage of water retained by the soil being increased from 32 to 39 per cent by the puddling process.

Therefore, in preparing the samples for a determination of the moisture equivalents, care was taken not to saturate the samples, and to stir the soil only enough to insure the distribution of the water throughout the sample.

TABLE III.—*Effect of initial water content on the moisture equivalent of soils.*

Soil type.	Approximate initial moisture content.	Moisture content after test.	Soil type.	Approximate initial moisture content.	Moisture content after test.
	Per cent.	*Per cent.*		*Per cent.*	*Per cent.*
Leonardtown loam (good)..	15	12.0	Norfolk sand (subsoil).....	10	7.4
	15	12.1		10	7.3
	20	11.5		15	7.0
	20	10.9		15	7.1
	25	11.7		20	7.0
	25	11.8		20	7.0
	Puddled.	14.0		Puddled.	7.4
	Puddled.	11.7		Puddled.	7.3
	15	12.4	Cecil clay (subsoil).....	35	32.9
	15	12.6		35	33.1
	20	11.4		40	34.1
	20	11.3		40	34.3
	25	11.8		43	35.0
	25	11.7		43	34.8
	Puddled.	11.9		Puddled.	39.2
	Puddled.	12.1		Puddled.	39.0

EFFECT OF SPEED ON THE MOISTURE EQUIVALENT.

A third series of measurements was made to determine for different soils the relation between the centrifugal force employed and the amount of moisture retained by the soils. If any definite and simple relation exists, then it would be possible to make the moisture equivalent determinations at any suitable speed and reduce the results to some standard condition, such as, for example, the retentivity of the soil when subjected to a force of 1,000 times the force of gravity. Such a relation would also enable us to calculate the amount of moisture which would become available when the pulling force is increased by a known amount.

The results of the experiments are given in Tables IV and V. In Table IV the different speeds employed are given at the heads of the columns, with duplicate determinations of the corresponding moisture equivalents below. The same arrangement exists in Table V, except that the means of the duplicate determinations are given. It will

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be seen in Table IV that doubling the speed, which quadruples the centrifugal force, reduces the moisture content of the Dunesand only from 3.0 to 2.6 per cent. In the case of this sand the capillary spaces are relatively large in size and few in number, so that it seems probable that the lowest speed employed is sufficient to reduce the moisture content mainly to the form of a thin film on the surface of the soil grains, so that the effect of quadrupling the force is small. In all the other soils there is a well-defined and progressive decrease in the moisture content as the speed increases. The results of Table IV indicate that the Leonardtown loam, good, and the Leonardtown loam, poor, are distinctly different in their relation to moisture.[a] Sample No. 4983, in Table V, is seen also to differ from the other soils of the series, giving up its moisture much more readily with increasing speeds.

TABLE IV.—*Effect of speed on moisture equivalent.*

Soil type.	Revolutions per minute.											
	2,700.		3,000.		3,200.		4,100.		4,200.		5,500.	
	P. ct.	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*
New Mexico dunesand	3.0	3.0	2.9	2.7	2.9	3.0	2.9	2.7	2.6	2.6	2.7	2.6
Sassafras loam, good.....	18.5	18.7	17.8	16.1	15.5	15.0	15.0	15.0	14.1	14.0	12.4	12.7
Leonardtown loam, good..	18.1	18.0	16.5	16.5	15.0	15.4	13.4	13.8	14.1	14.3	12.1	12.1
Leonardtown loam, poor..	12.0	12.0	10.1	10.5	9.4	9.9	8.0	7.5	7.4	7.4	6.3	6.3

TABLE V.—*Effect of speed upon the moisture equivalent.*

No.	Type.	Speed—revolutions per minute.		
		4,300.	5,000.	5,500.
		Per ct.	*Per ct.*	*Per ct.*
7233	Hagerstown stony loam.....	16.9	15.0	14.6
6534	Hagerstown sandy loam.....	12.2	11.0	9.9
4952	Hagerstown loam.....	21.8	20.8	18.4
9248	Hagerstown loam.....	18.3	17.5	16.5
10212	Hagerstown silt loam.....	17.9	16.5	15.8
4983	Hagerstown shale loam.....	31.6	25.0	17.3
4962	Hagerstown clay loam.....	24.1	23.4	21.5
4966	Hagerstown clay loam.....	26.0	25.5	24.8

A simpler way of comparing these results is to be found in the graphical arrangement shown in figure 1, for which we are indebted to Mr. Buckingham, of this laboratory. In this diagram the moisture equivalents are plotted as ordinates, while the abscissas are proportional to the reciprocal of the centrifugal force. If all of the moisture could be thrown out of the soil by an infinite centrifugal force, the moisture equivalent would be zero when the centrifugal force is infinite, i. e., when the reciprocal of the centrifugal force (plotted as abscissas) is zero. In this case all of the graphs would pass through the origin. However, between the limiting values of

[a] See Bulletin No. 22, Bureau of Soils, p. 34.

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the centrifugal force employed in these experiments it will be seen that in nearly every case a *linear* relation exists between the moisture equivalent and the reciprocal of centrifugal force. These linear graphs when produced do not pass through the origin, but, on the other hand, *the slope of these graphs is in nearly every case the same.*

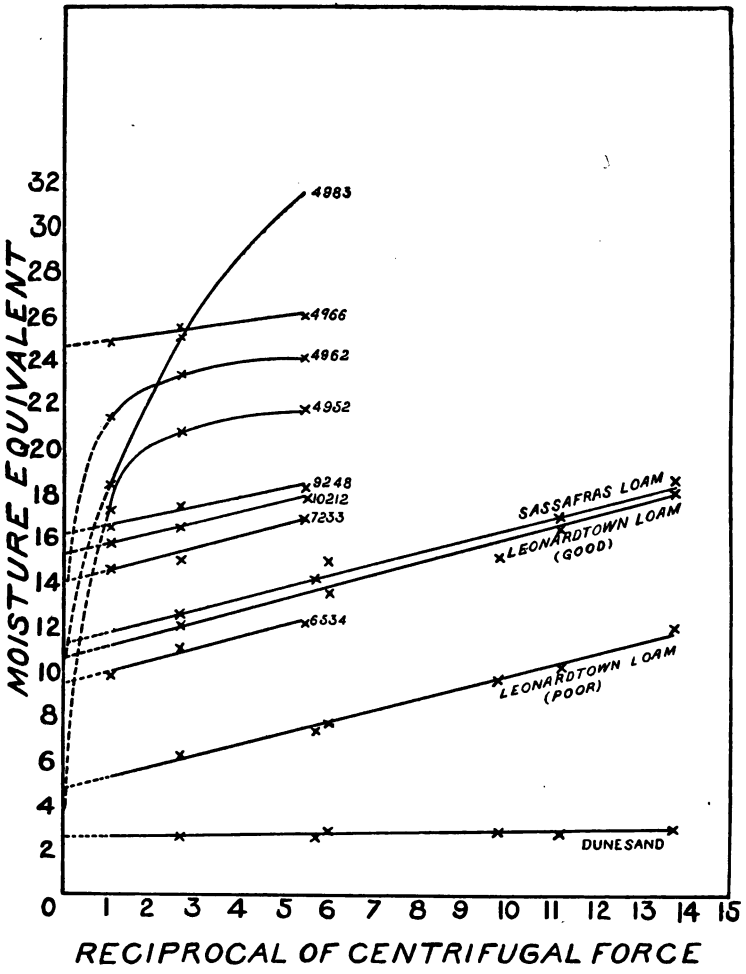

FIG. 1.—Relation of the moisture equivalent to the force employed.

Consequently we may represent within certain limits the relation between the moisture equivalent m and the centrifugal force f as follows:

$$m = m_0 + \frac{a}{f}$$

where m_0 is the intercept on the axis of ordinates of the prolongation of the linear part of the curve, and a is the slope. The constant

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a may be computed from the data given in Table IV (the dunesand excepted), from which we get $a=6{,}100$, expressed in terms of the force of gravity. When a soil is in equilibrium with a force f_1, the amount of moisture which is liberated when the centrifugal force is increased from f_1 to f_2 is

$$m_1 - m_2 = a\left(\frac{1}{f_1} - \frac{1}{f_2}\right)$$

or the moisture set free is proportional to the difference of the reciprocals of the two centrifugal forces, and *is independent of the initial moisture content.* For example, if $f_1=1{,}000$, $f_2=2{,}000$, $a=6{,}100$, then $m_1 - m_2=3.05$, or 3 per cent of water would be set free when the centrifugal force is increased from 1,000 to 2,000 times the force of gravity.

It must be distinctly understood that this relation has been tested for only a few soils, and that it can hold only between certain limits. It is evident from the diagram that the linear relation must fail at very high velocities. In fact, samples 4962 and 4952 show a marked tendency in this direction at the highest speed employed. At very low speeds, also, the linear relation no longer holds. The dunesand and sample 4983 are also exceptions, so far as a uniform value for the coefficient a is concerned. But even with such limitations this relation, if it is found to be applicable to other soils, will prove of value in adjusting moisture equivalents to a common basis, and in determining the amount of water available when the force is increased by a definite amount. The fact that the amount of water liberated from a soil in equilibrium with a given force, when the force is increased by a definite amount, is, between certain limits, independent of the initial moisture content, gives us a new point of view regarding the availability of the moisture of different soils.

These experiments have not been carried sufficiently far to reduce the moisture content of the soils to a point corresponding to drought conditions, but it appears doubtful from these experiments whether the linear relation would hold at speeds very much higher than these employed. The subject is worthy of extended investigation, especially at high velocities.

ACCURACY OF THE DETERMINATIONS OF THE MOISTURE EQUIVALENT.

The accuracy of the determinations of the moisture equivalents can best be judged from Table VI, in which is given a series of determinations made on different dates. It will be seen that a good agreement is generally obtained from different runs, the moisture equivalents usually agreeing within 0.5 per cent of moisture. Samples 8969 and 9332 show, however, a steady decrease in the moisture equivalents for successive determinations. The samples of these soils were small,

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so that it was necessary to save the soil used in a determination of the moisture equivalent, for use in subsequent measurements. It is, therefore, possible that the repeated oven drying, which a part of the sample received, changed the character of the soil material sufficiently to produce the diminution of the moisture equivalent observed.

TABLE VI.—*Duplicate moisture equivalent determinations on different dates.*

[5,000 revolutions per minute.]

Sample No.	Type of soil.	First determination.	Second determination.	Sample No.	Type of soil.	First determination.	Second determination.
		Per ct.	*Per ct.*			*Per ct.*	*Per ct.*
9248	Hagerstown loam:			8503	Miami silt loam—Contd.		
	July 11	17.3	17.2		July 20	18.3	18.5
	Aug. 8	17.8	17.9		July 21	18.6	.....
	Aug. 10	17.6	17.3	5014	Miami clay:		
4962	Hagerstown clay loam:				July 21	17.7	17.9
	Aug. 8	23.4	23.5		Aug. 7	18.9	18.7
	Aug. 11	23.4	23.4	8398	Marshall sandy loam:		
4966	Hagerstown clay loam:				July 18	13.0	13.5
	July 12	24.9	24.9		July 22	13.3	13.6
	Aug. 8	26.5	26.2	9493	Marshall clay loam:		
	Aug. 11	25.6	25.3		July 19	23.3	22.9
8969	Miami stony loam:				July 21	23.4	.....
	July 18	17.7	15.9	9332	Oswego loam:		
	July 22	15.1	15.3		July 31	20.7	20.7
	Aug. 5	14.1	14.5		Aug. 7	19.8	19.7
5008	Miami gravelly loam:				Aug. 9	18.0	18.1
	July 14	13.2	13.3	6917	Sedgwick clay loam:		
	July 20	13.5	13.6		July 28	21.3	22.2
5006	Miami loam:				July 31	22.1	22.1
	July 20	17.7	17.7	6632	Delavan silt loam:		
	Aug. 7	18.0	18.0		Aug. 10	26.8	26.8
	Aug. 9	17.5	17.8		Aug. 2	24.1	23.5
8506	Miami silt loam:				Aug. 4	26.3	26.3
	July 15	18.3	18.7				

MOISTURE EQUIVALENTS OF TYPICAL SOILS.

With the experiments described in the foregoing pages as a basis, determinations were made under uniform conditions of the moisture equivalents of representative samples of each of the important soil types established by the Bureau. These determinations are given in Table VII, arranged in the form of correlated series, so far as these series have been established.

The determinations were all made at a speed of 5,000 revolutions per minute, which would correspond to a centrifugal acceleration equal to 2,940 times that of gravity. The determination of the speed was not accurate to more than 1 per cent, which means a variation of 2 per cent in the centrifugal force, since the speed enters as the square in the equation. The centrifugal force employed in these measurements would then be

$$f=(2940\pm 60)\ g$$

where g represents the force of gravity.

The amount of soil used covered the bottom of the cylindrical cup (internal diameter 4.7 cm.) to a depth of approximately 5 mm.

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When large amounts of soil were used, it was found in some of the more retentive soils that there was a tendency for a part of the water to accumulate upon the top of the soil instead of passing through the soil and escaping through the perforated bottom of the cup. No trouble was experienced in this way when the layer of soil did not exceed 0.5 cm. in thickness.

At the end of the run a moisture determination was made immediately of each sample of soil used in the test, the whole of the sample being employed for this purpose. The moist samples were quickly weighed and then dried for eight hours in an oven maintained at a temperature of 108° C., and then weighed again. Such a temperature in an oven is easily maintained by the use of toluol in the so-called water oven. If the apparatus is provided with a good Allihn return condenser, very little toluol escapes, and the apparatus works very satisfactorily.

In Table VII the first column following the type names gives the moisture equivalent; the second the percentage of organic matter, determined by the chromic acid combustion method; the remaining columns give the mechanical composition. The limits of the diameters of the particles in each group are given in italics under the group number.

TABLE VII.—*Moisture equivalents and mechanical composition of typical soils.*

No.	Type.	Moisture equivalent.	Organic matter.	(1) *2–1 mm.*	(2) *1–0.5 mm.*	(3) *0.5–0.25 mm.*	(4) *0.25–0.1 mm.*	(5) *0.1–0.05 mm.*	(6) *0.05–0.005 mm.*	(7) *0.005–0.0 mm.*
		P. ct.	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*
9107	Norfolk coarse sand	4.6	0.9	9.6	35.3	19.1	16.4	7.2	7.3	4.8
8522	Norfolk sand	3.6	1.0	2.0	8.5	19.0	52.6	7.1	5.8	4.7
8589	Norfolk fine sand	3.8	0.8	0.0	0.7	13.7	69.0	5.4	7.9	3.0
5665	Norfolk sandy loam	6.5	0.7	4.3	12.7	18.3	33.1	6.6	20.0	5.6
8706	Norfolk fine sandy loam	6.8	1.3	0.0	0.5	4.8	54.6	13.4	18.1	8.5
8682	Norfolk loam	7.7	1.9	0.3	8.9	16.2	16.7	5.4	42.5	9.7
5493	Norfolk silt loam	11.1	1.2	0.0	1.4	2.8	8.9	6.7	68.3	12.0
8530	Portsmouth sand	7.1	3.0	1.9	16.8	26.0	31.7	5.5	6.7	11.3
8537	Portsmouth sandy loam	18.6	10.9	0.8	4.9	7.3	31.7	13.0	23.6	18.7
10666	Portsmouth fine sandy loam	11.8	1.0	0.3	1.5	2.0	45.4	15.1	24.2	12.6
8022	Portsmouth loam	10.6	2.7	0.0	0.3	0.3	14.7	24.5	43.5	16.8
7848	Orangeburg sandy loam	5.7	1.7	9.5	20.8	13.3	22.7	15.4	6.4	11.6
8594	Orangeburg fine sandy loam	3.2	0.4	0.0	0.2	2.2	69.6	8.3	16.3	3.3
8339	Orangeburg clay (clay loam)	21.4	0.5	5.2	4.5	4.9	9.3	23.4	24.8	28.8
10087	Houston silt loam	13.7	1.7	1.0	1.2	1.0	5.8	15.1	63.4	12.3
10574	Houston black clay loam	32.4	3.7	0.3	0.6	0.8	12.1	17.1	42.5	26.6
7887	Houston clay (silty)	22.5	1.3	0.5	1.7	2.8	13.3	9.1	45.9	26.4
10083	Houston black clay	33.2	1.4	0.5	0.9	0.6	2.2	6.1	56.6	33.4
7753	Vernon sand	3.6	0.5	0.0	7.4	25.0	45.3	13.4	5.4	3.6
10118	Vernon fine sand	4.3	0.2	0.0	0.1	0.2	49.4	42.1	5.9	2.1
7757	Vernon sandy loam	10.3	0.8	0.2	8.8	17.9	25.6	22.8	13.2	11.3
7737	Vernon fine sandy loam	12.3	0.8	0.0	0.7	0.5	2.6	47.0	42.3	6.7
7749	Vernon silt loam	19.8	0.9	0.1	0.1	0.0	0.3	16.4	72.2	10.7
7763	Vernon clay (loam)	23.1	1.1	0.5	0.2	1.3	3.6	27.1	51.1	15.9
6442	Yazoo loam	18.9	1.3	0.3	0.9	0.7	3.7	19.9	64.1	10.1
6430	Yazoo clay	31.7	1.4	0.0	0.1	0.2	1.6	4.0	63.2	31.1
5741	Cecil sand	5.1	0.8	7.6	17.7	13.6	25.0	12.0	17.4	6.1
5327	Cecil sandy loam	7.7	1.2	14.7	15.6	9.8	21.3	13.1	17.8	7.9
7185	Cecil loam	16.6	1.9	1.9	5.1	4.8	15.3	9.6	39.6	23.6
4983	Cecil mica loam	12.2	1.9	7.8	4.3	2.2	14.4	30.9	33.3	7.8
5719	Cecil silt loam	8.3	0.6	2.6	1.7	0.7	3.4	6.1	74.2	11.8
5727	Cecil clay (clay loam)	21.2	2.0	1.4	2.7	2.0	7.1	10.1	44.8	31.6

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TABLE VII.—*Moisture equivalents and mechanical composition of typical soils*—Continued.

No.	Type.	Moisture equivalent.	Organic matter.	(1) 2–1 mm.	(2) 1–0.5 mm.	(3) 0.5–0.25 mm.	(4) 0.25–0.1 mm.	(5) 0.1–0.05 mm.	(6) 0.05–0.005 mm.	(7) 0.005–0.0 mm.
		P. ct.	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*
5904	Penn sandy loam	9.3	0.9	2.2	11.6	13.4	27.6	11.8	21.0	12.1
5898	Penn loam	17.3	1.3	2.6	7.6	7.0	14.3	7.8	37.4	22.8
7703	Penn clay (clay loam)	17.9	1.3	1.4	2.7	2.1	5.0	14.0	42.6	32.2
7240	Dekalb stony loam	12.8	2.5	3.4	11.1	9.0	17.7	10.8	33.4	14.6
10025	Dekalb sandy loam	11.7	1.3	0.5	11.0	26.1	24.2	4.3	17.8	16.1
10216	Dekalb fine sandy loam	12.8	1.0	0.4	1.4	8.8	44.2	8.1	25.0	11.9
10154	Dekalb clay loam	21.6	2.3	0.4	0.7	2.1	6.6	14.8	48.6	26.9
7233	Hagerstown stony loam	15.0	1.6	2.7	4.9	3.6	7.3	14.1	45.1	22.1
6534	Hagerstown sandy loam	11.0	1.0	0.4	5.0	8.8	23.4	20.2	33.0	9.4
4952	Hagerstown loam	20.8	1.4	2.1	3.4	3.4	6.8	12.4	57.2	14.9
9248	Hagerstown loam	17.5	1.0	1.0	1.8	1.4	7.4	18.6	49.9	19.7
10212	Hagerstown silt loam	16.5	1.0	0.3	0.6	1.5	9.1	10.5	60.3	17.4
4983	Hagerstown shale loam	25.0	2.6	13.1	5.1	2.0	3.8	7.9	55.5	11.7
4962	Hagerstown clay loam	23.4	2.2	1.0	2.7	2.6	6.7	10.6	61.7	14.3
4966	Hagerstown clay loam	25.5	1.3	1.9	1.8	1.2	2.5	6.3	69.6	17.0
9037	Hagerstown clay	23.0	1.1	0.8	1.8	1.1	2.5	4.1	54.9	34.8
6024	Clarksville stony loam	13.7	0.3	1.5	2.1	1.2	3.2	8.0	67.9	16.5
6006	Clarksville loam	18.5	1.3	0.1	0.1	0.4	17.1	23.6	39.4	19.0
6018	Clarksville silt loam	15.1	1.2	1.2	1.4	0.9	2.9	5.6	73.2	14.8
6008	Clarksville clay loam	20.8	1.9	0.2	0.5	0.7	3.7	3.9	71.1	20.0
10184	Clarksville clay	31.7	2.3	0.4	0.9	0.5	1.2	4.5	54.0	37.7
6092	Miami sand	4.3	1.9	0.5	9.1	38.1	41.3	1.9	5.2	3.7
6696	Miami fine sand	4.7	1.1	0.3	17.4	26.0	35.6	10.3	5.9	4.5
9606	Miami sandy loam	7.0	2.1	3.4	11.8	15.0	33.2	14.7	14.4	7.3
9626	Miami fine sandy loam	13.3	1.7	1.6	5.1	7.8	25.4	15.2	32.3	12.4
8969	Miami stony loam	15.4	4.7	2.1	7.3	5.5	7.4	16.5	44.8	16.5
5008	Miami gravelly loam	13.4	0.8	5.6	11.4	9.5	18.0	15.9	26.1	13.2
5006	Miami loam	17.7	2.2	1.6	10.7	10.7	21.7	19.8	22.0	13.3
8506	Miami silt loam	18.5	0.9	0.3	1.2	0.8	1.2	6.4	79.6	16.7
5014	Miami clay loam	18.3	1.2	0.7	1.6	1.8	4.2	11.2	68.4	12.0
9505	Marshall sand	7.2	1.7	2.5	16.7	19.1	34.3	6.8	10.6	10.2
8804	Marshall fine sand	5.4	1.3	0.6	2.2	7.7	57.8	21.5	4.2	5.9
8398	Marshall sandy loam	13.4	3.5	4.6	14.0	12.7	22.5	10.1	24.0	12.1
8418	Marshall gravelly loam	19.7	7.8	7.3	20.2	10.8	8.7	5.8	28.9	18.0
9158	Marshall stony loam	30.2	3.9	2.3	8.7	10.4	28.7	15.1	22.8	12.1
8788	Marshall loam	18.8	2.1	1.5	6.4	8.0	19.5	16.3	23.3	24.7
8728	Marshall silt loam	26.9	2.1	0.2	0.9	0.5	0.6	3.7	76.3	17.7
9493	Marshall clay loam	23.3	5.1	0.2	4.1	4.9	8.2	4.3	52.8	25.4
8453	Marshall clay	36.4	5.4	0.2	1.7	1.7	4.3	2.0	49.3	40.8
8664	Sioux sand	4.9	2.4	0.4	14.2	30.7	43.5	1.1	5.9	4.4
8670	Sioux sandy loam	13.8	3.3	0.6	13.6	16.1	20.4	9.7	28.1	12.5
9535	Sioux fine sandy loam	21.4	2.6	1.2	4.5	4.9	16.9	21.9	38.6	11.8
9174	Sioux clay	38.4	5.2	0.0	0.3	0.8	5.8	4.5	32.1	56.6
9288	Dunkirk gravelly loam	7.9	2.7	17.4	18.1	12.6	15.7	9.2	17.4	9.6
9296	Dunkirk sandy loam	10.5	2.2	0.8	3.4	3.9	42.7	26.1	13.0	9.8
9286	Dunkirk clay	37.8	3.7	0.9	1.8	1.2	5.3	5.9	31.6	53.1
9334	Oswego fine sandy loam	9.7	1.3	0.1	0.9	1.1	26.1	31.2	29.3	11.1
9332	Oswego loam	19.4	2.7	0.7	1.8	0.8	3.6	15.8	61.1	16.2
9340	Oswego silt loam	11.3	1.2	0.3	0.4	0.3	1.9	9.6	74.1	13.2
6921	Sedgwick sandy loam	7.9	1.3	0.3	8.9	18.6	32.3	18.6	14.0	7.0
6909	Sedgwick loam	15.4	2.3	0.3	5.3	9.6	12.2	11.7	51.4	9.4
6917	Sedgwick clay loam	21.9	1.0	0.1	1.5	2.3	5.3	10.4	66.0	14.2
6919	Sedgwick black clay loam	15.2	1.3	0.3	1.0	1.3	8.3	31.2	48.6	9.1
7978	Memphis silt loam	12.9	1.2	0.3	0.8	0.6	0.7	2.9	83.8	10.6
6632	Delavan silt loam	25.6	2.9	0.3	0.9	0.7	1.0	8.9	69.4	18.8
7008	Marion silt loam	14.7	1.7	0.1	1.0	0.7	0.7	3.0	82.9	11.5
7009	Marion silt loam	14.7	0.7	1.1	1.8	1.0	1.1	3.5	79.8	11.8
7385	Waverly silt loam	24.4	2.0	0.7	2.6	1.1	2.7	7.6	62.9	22.2
4445	Maricopa gravelly loam	8.9	0.2	11.3	11.0	12.0	15.0	28.4	16.6	5.7
4494	Maricopa sandy loam	13.8	3.0	Tr.	2.3	15.0	27.7	28.2	13.5	13.0
8134	Maricopa silt loam	36.2	1.1	0.0	0.1	0.1	0.9	2.1	73.0	23.8
4486	Maricopa clay	19.1	0.4	1.3	4.0	10.2	19.1	23.1	19.4	22.8
4887	Fresno sand	3.0	0.4	0.9	15.8	31.3	22.6	18.1	8.2	3.0
4683	Fresno sandy loam	5.3	0.5	Tr.	1.0	3.9	23.5	31.7	32.9	7.0
5081	Fresno fine sandy loam	12.8	0.6	Tr.	3.0	3.8	16.9	35.4	36.3	4.7
5790	Yakima sand	5.4	0.3	0.3	1.5	9.6	38.9	40.6	5.8	3.1
7690	Yakima fine sand	10.0	0.8	0.2	2.2	5.8	24.8	22.6	37.8	6.4
5364	Yakima sandy loam	13.4	0.7	0.9	3.3	7.3	23.0	22.9	33.2	9.2
7509	Yakima silt loam	23.6	2.3	0.5	0.8	0.6	1.8	7.2	81.3	7.5
9136	Yakima loam	16.2	1.7	Tr.	0.5	0.6	13.0	35.0	34.0	16.6
5325	Cecil clay (subsoil)	36.2	0.3	0.9	4.0	4.1	9.4	6.0	16.2	59.8
5762	Iredell clay loam (subsoil)	40.5	0.4	1.4	1.6	1.7	8.9	8.5	17.8	59.8

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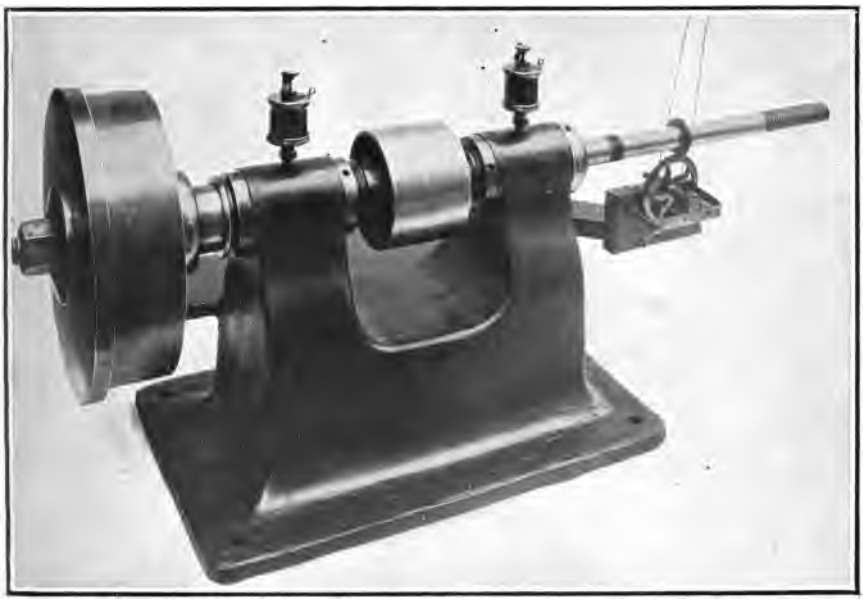

FIG. 1.—CENTRIFUGAL MACHINE USED FOR DETERMINING MOISTURE EQUIVALENTS.

FIG. 2.—HEAD OF CENTRIFUGAL MACHINE, SHOWING CYLINDRICAL CUPS WITH PERFORATED BOTTOMS FOR HOLDING THE MOIST SAMPLES OF SOIL.

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RELATION OF MECHANICAL COMPOSITION TO THE MOISTURE EQUIVALENT.

In order to determine whether a definite relation could be found between the mechanical composition of the soils and the moisture equivalents, the data given in Table VII were examined by the method of least squares. It was *assumed* that the sands, silt, clay, and organic matter all helped to hold the moisture in the soil, and it was further *assumed* that the retentive power of each constituent was directly proportional to the amount of that constituent present. The object was then to determine the moisture retentivities of the various constituents. The observational equations, in accordance with the above assumption, were of the form

$$\begin{aligned} &A_1Z_1+B_1Z_2+C_1Z_3+D_1Z_4+E_1Z_5=M_1,\\ &A_2Z_1+B_2Z_2+C_2Z_3+D_2Z_4+E_2Z_5=M_2,\\ &\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\\ &A_nZ_1+B_nZ_2+C_nZ_3+D_nZ_4+E_nZ_5=M_n, \end{aligned} \qquad (1)$$

in which

A = per cent, groups 1, 2, 3 (2–0.25 mm.),
B = per cent, groups 4, 5 (0.25–0.05 mm.),
C = per cent, group 6 (0.05–0.005 mm.),
D = per cent, group 7 (0.005–0 mm.),
E = per cent, organic matter,
M = moisture equivalent,

and Z_1, Z_2, Z_3, Z_4, Z_5, were the unknown coefficients, whose values we wished to determine.

Each soil examined gave an observational equation of this form, amounting to 104 equations in all. Owing to the inherent differences in the *character* of the clay and of the organic matter as well as the observational errors, these equations could not be exactly satisfied by one set of values of the Z-coefficients. It was therefore necessary to determine by the method of least squares the most probable values of the Z-coefficients; that is, the best values that could be deduced from the given observations. The most probable values of the coefficients as determined from the 104 equations were:

$$\begin{aligned} Z_1&=0.022\\ Z_2&=0.002\\ Z_3&=0.130\\ Z_4&=0.622\\ Z_5&=0.627 \end{aligned}$$

The equation expressing the relation between the mechanical composition of a soil and its moisture equivalent, as determined from the 104 observational equations, would then be

$$0.022A + 0.002B + 0.13C + 0.622D + 0.627E = M. \qquad (2)$$

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By substituting the above values of the Z-coefficients in each observational equation, we determined the difference between the observed and calculated values of the moisture equivalent in each case. From these residuals we calculated the probable error[a] of a single determination of the moisture equivalent by means of equation (2), which was found to be

$$r = \pm 3.1.$$

The equation expressing the relation between the moisture equivalent and the mechanical composition for the 104 soils becomes, when the probable error is included,

$$0.022A + 0.002B + 0.13C + 0.622D + 0.627E = M \pm 3.1. \quad (3)$$

According to this equation, equal quantities of organic matter and clay have nearly the same effect on the moisture equivalent. For the centrifugal force employed, the moisture equivalent, expressed in per cent, is proportional to about 0.62 of the total percentage of clay and organic matter together. The silt has only about one-fifth the effect of the clay and the organic matter, the moisture equivalent being proportional to 0.13 of the silt content. The coefficients of the sand groups are both very small, as we should expect. An anomaly arises, however, in the case of these two groups, the coarser sand having apparently a greater influence on the retention of moisture than the finer grades of sand. This results from the fact

[a] The term "probable error" is here used in its technical sense, and serves as a measure of the accuracy of the observations, in this case, of both the moisture equivalent and the mechanical composition. As here used, it includes also the *departures* due to the lack of uniformity in the character of the clay and organic matter in the different soils considered. The uncertainty resulting from this lack of uniformity would be more properly expressed by the term "probable departure," since it is not due to the observational errors. However, it is not possible in a series of observations of this kind to separate these two terms, so that the term probable error has been used in this inclusive sense.

The term probable error should not be interpreted to mean "the most probable error," or "the most probable value of the actual error." In any series of errors, the probable error has such a value that the number of errors greater than it is the same as the number of errors less than it. In other words, the chances are even that an observation selected at random will have an error greater than or less than the probable error.

It should be emphasized that the probable error is concerned with errors of an accidental character—errors which are as likely to lead to results too large as to results too small. A single determination of the probable error can not reveal the existence of a constant error, nor show whether the assumption made regarding the relation between the observed quantities is correct. Errors of this kind must be detected by changing the form of the observational equation, and determining the probable error for each form of equation assumed. The form giving the smallest probable error most nearly represents the relation sought.

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that the soils vary greatly in character, so that the individual peculiarities of the soils tend to mask the true values of coefficients that are very small.

The slight influence of the sand groups is shown by the fact that a change of 50 per cent in the amount of coarse sand amounts to a change of but 1 per cent in the moisture equivalent. We can consequently ignore the influence of the sands in an approximate equation, whence equation (3) becomes,

$$0.13C + 0.62(D+E) = M \pm 3. \qquad (4)$$

NORFOLK AND PORTSMOUTH SERIES.

In the case of a well-defined series of soils in which the material is mainly derived from the same source one would expect a more definite relation between the mechanical composition and the moisture equivalent than would be the case for soils derived from different rocks under widely varying conditions. We have accordingly determined by the method of the least squares the coefficients for the Norfolk and Portsmouth series combined, which are quite similar in character, save that the Portsmouth includes heavier soils and carries more organic matter. The coefficients of the sands were taken equal to zero, and for the other coefficients the following values were obtained:

$$Z_3 = 0.042$$
$$Z_4 = 0.590$$
$$Z_5 = 0.528$$

The equation of the combined Norfolk and Portsmouth series is then

$$0.04C + 0.59D + 0.53E = M \qquad (5)$$

A comparison of the observed moisture equivalents with those calculated with the aid of equation (4) is given in the following table:

TABLE VIII.—*Comparison of observed and calculated moisture equivalents of the Norfolk and Portsmouth series.*

Sample number.	*C* (0.05–0.005).	*D* (0.005–0.0).	*E* Organic matter.	Moisture equivalent.		
				Calculated.	Observed.	Residuals.
9107	7	5	0.9	3.7	4.6	−0.9
8522	7	6	1.0	4.4	3.6	+0.8
8589	8	3	.8	2.5	3.8	−1.3
5665	19	5	.7	4.1	6.5	−2.4
8706	18	8	1.3	6.2	6.8	−0.6
8682	42	10	1.9	8.7	7.7	+1.0
5493	68	12	1.2	10.6	11.1	−0.5
8530	7	11	3.0	8.3	7.1	+1.2
10666	24	13	1.0	9.2	11.8	−2.6
8022	44	17	2.7	13.3	10.6	+2.7
8537	24	19	10.9	18.0	18.6	−0.6

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From the residuals in Table VIII we can calculate the probable error of a single determination, which we find to be

$$r=1.09$$

which means that if the soils employed in the measurements were typical, then the chances are even that the moisture equivalent of any other typical soil can be determined from equation (5) within 1.1 of its absolute value. The characteristic equation of the combined Norfolk and Portsmouth series then becomes

$$0.04C+0.59D+0.53E=M\pm1.1 \qquad (6)$$

Comparing this equation with equation (4), we see that the ratio of the probable errors is 1:2.7. In other words, equation (6) expresses the relation between the mechanical composition and the moisture equivalent for the Norfolk and Portsmouth series with an accuracy 2.7 times that of the equation (4) for the 104 soils. The coefficients for the Norfolk and Portsmouth series are all smaller than in equation (4), the organic matter coefficient being reduced from 0.63 to 0.53, the coefficient for the clay group from 0.62 to 0.59, while the greatest change occurs in the silt group, which is reduced from 0.13 to 0.04.

MARSHALL SERIES.

For the Marshall series, omitting samples 8418 and 9158, which are said not to be typical, the following values of the Z coefficients were obtained:

$$Z_3=\ 0.20$$
$$Z_4=\ 0.62$$
$$Z_5=-0.11$$

The equation for the Marshall series is then

$$0.20C+0.62D-0.11E=M \qquad (7)$$

A comparison of the observed moisture equivalents with those calculated from equation (7) is given in Table IX.

TABLE IX.—*Comparison of the observed and calculated moisture equivalents of the Marshall series.*

Sample number.	C (0.05–0.005).	D (0.005–0.0).	E organic matter.	Moisture equivalent.		
				Calculated.	Observed.	Residuals.
9505	11	10	1.7	8.2	7.2	+1.0
8804	4	6	1.3	4.4	5.4	−1.0
8398	24	12	3.5	11.8	13.4	−1.6
8788	23	25	2.1	19.8	18.8	+1.0
8728	76	18	2.1	26.1	26.9	−0.8
9493	53	25	5.1	25.5	23.3	+2.2
8453	49	41	5.4	34.6	36.4	−1.8

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For this series the probable error in the calculation of the moisture equivalent of a typical sample from its mechanical analysis is

$$r=1.04$$

which is slightly less than the probable error for the Norfolk and Portsmouth series.

The equation of the Marshall series then becomes

$$0.20C+0.62D-0.11E=M+1.0 \qquad (8)$$

MOISTURE EQUIVALENT COEFFICIENTS OF CECIL, HAGERSTOWN, MIAMI, AND VERNON SERIES.

In Table X the coefficients given above are summarized, together with the results of a number of calculations made in different ways upon other soil types. In the Cecil series, for example, the coefficients have been determined: (1) for the silt, and for the clay and organic matter combined; (2) for the silt, clay, and organic matter separated; (3) for the clay and organic matter, assuming that the silt and coarser grades have no effect on the moisture equivalent.

TABLE X.—*Summary of moisture equivalent coefficients.*

Series.	Silt.	Clay.	Organic matter.	Clay + organic matter.	Probable error, moisture equivalent.
All	0.13	0.62	0.63	.....	3.1
Norfolk and Portsmouth	.04	.59	.53	.....	1.1
Marshall	.20	.62	.11	.....	1.0
Cecil	.03	.....	.....	0.62	1.7
Do	.06	.39	3.6	.....	1.2
Do	.....	.44	3.6	.....	.7
Hagerstown	.35	.....	.....	.06	2.4
Do	.25	.11	2.4	.....	2.0
Do	.....	.61	4.7	.....	3.2
Miami	.09	.....	.....	.69	2.2
Do	.....	.70	1.8	.....	2.7
Vernon	.17	.....	.....	.74	.8
Do	.....	1.4	.002	.....	2.4

According to these results, the moisture equivalents of the Cecil series could best be expressed in terms of the mechanical analysis by considering only the clay and organic matter, since on this assumption we obtain the smallest probable error. This illustrates the danger of generalizing from a small number of observations in a question of this kind, since no one would admit the effect of the silt to be nil. It will be noticed, also, that in all other instances we get the highest probable error on this assumption. The danger just spoken of is especially well illustrated in the Hagerstown series, where the reductions would indicate that the clay had less effect than the silt in the retention of moisture. This relation is altogether improbable, and undoubtedly would not appear in the reductions if

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a suitable number of samples were considered. With this precaution, this method of reduction could be used to determine to what extent one series differs from another in the relation of its silt, clay, and organic matter to the retention of moisture. This would, however, resolve itself into a special study of the characteristics of the different series. The present reductions emphasize the individuality of different soils.

SUMMARY.

In the comparative study of soils it is important to supplement the mechanical analyses by quantitative measurements of other characters, especially those relating to the movement and retention of moisture.

The present paper deals with a method of determining the amount of water which different soils are capable of retaining when the soil moisture is subjected to a constant measured force sufficient in magnitude to remove the moisture from the larger capillary spaces. The method is as follows: The soils under investigation are first thoroughly moistened, and are then placed in the perforated cups of a centrifugal machine, where they are subjected to a constant centrifugal force until they cease to lose moisture. The percentage of water remaining in the soil is then determined.

It is possible to reduce the moisture content of a soil in this way so that it is no greater than the moisture content of the soil under favorable field conditions. By this method, then, it is possible to determine the retentive power of different soils for moisture when acted upon by the same definite force, comparable in magnitude with the pulling force to which the soil moisture is subjected in the field. Furthermore, this method of comparing the relation of soils to moisture avoids to a large extent, if not entirely, the errors due to differences in packing, since the soils are packed by centrifugal force, which acts upon each individual particle. This is further safeguarded by the high speed employed, which is sufficient to remove the moisture from any large capillary spaces that may possibly be formed.

The method has the further advantage that the force employed can be accurately determined by measuring the radius of rotation and the speed of the machine. A wide range in the force used can also be easily secured simply by changing the speed of the machine, since the centrifugal force increases as the square of the speed.

The maximum percentage of moisture which a soil can retain when in equilibrium with a definite force we have designated as the "moisture equivalent" of that soil for the particular force employed. It logically follows that a series of soils which have thus been brought

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into equilibrium with the same force will be in capillary equilibrium with one another when brought into contact, and that no capillary movement of moisture will take place between them. In other words, the moisture equivalents of a series of soils represent the moisture contents which those soils must have in order to make it equally difficult to remove a very small additional amount of moisture from any of the soils. It is from this point of view that the determination of the moisture equivalent becomes of especial importance in the comparison of the moisture contents of different soils under growing crops.

The moisture equivalents of over 100 samples of type soils have been determined, employing for this purpose a centrifugal force about 3,000 times the force of gravity. These moisture equivalents vary from 3.6 per cent in the coarser sandy soils to 46.5 per cent in the case of a heavy clay subsoil.

These observations were reduced by the method of least squares to determine the influence of the sand, silt, and clay groups, and of the organic matter, upon the retention of moisture. It was found for the whole series that each per cent of clay or of organic matter in the soil corresponded to a retention of 0.62 per cent of moisture when the soil was subjected to a force 3,000 times that of gravity. Each per cent of silt, under similar conditions, corresponded to a retention of 0.13 per cent of moisture, and the coarser grades show practically no retentive action against this force. The "probable error" for these coefficients was rather high, and better results were obtained for smaller series of related soils, using a different set of coefficients. It is interesting to note that the organic matter, for the force employed, has a retentive power no greater than the clay group.

In investigating the influence of the speed upon the moisture equivalent it was found, for the series of soils examined, that between certain limits the amount of moisture set free when the pulling force is increased by a definite amount is the same for the different soils. In other words, when this series of moist soils is in equilibrium with a given force, and the force is then increased by a definite amount, the amount of water set free is independent of the initial water content. Within these limits, then, a sandy soil and a heavy soil of this series part with equal amounts of moisture.

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